TRANSACTIONS
OF THE
American Institute of Electrical Engineers

Vol. 49 | OCTOBER, 1930 | No. 4

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PUBLISHED QUARTERLY BY THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
IN JANUARY, APRIL, JULY, AND OCTOBER
33 West 39th St., New York, N. Y.

Cloth Covers, Subscription $10.00 per year, $3.00 per copy

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PREFACE

This is the final number of Volume 49 of the Quarterly TRANSACTIONS of the American Institute of Electrical Engineers, and contains the papers and committee reports presented at the Summer Convention held at Toronto, Ontario, Canada, June 23-27, as well as *The Status of the Young Engineer*, the address delivered by President Smith at that convention.

Parts 1, 2 and 3 of Volume 49 contain the index of authors as published in each separate issue. An index of authors and a subject index to Volume 49 are complete in this number.

Transmission System Relay Protection—III*

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Synopsis.—A paper was presented in 1919, followed by Part II in 1921, giving a résumé of the relay protective systems up to those dates. The various important developments since 1921 warrant a third paper on this subject. There has been a general realization of the importance of shortening the time for removing a fault, and this has led to the production of high-speed circuit breakers combined with very fast relays, the total time of clearing trouble being reduced to from two to eight cycles. There is a tendency towards types of relays and schemes which are inherently selective in operation, such as the "distance" relays, balanced or differential schemes, pilot wire relays, etc.

Due to the increased reliability of service and to the relative ease of obtaining selectivity and high speed of the relay protective system the growth of the use of parallel lines (usually in pairs) has been rapid. Back-up protection against through short circuits or failures of relays or breakers at the succeeding stations is growing in use and the necessary relays are being added unless the scheme adopted inherently has this covering protection.

Due to its fundamental advantages of the detection of a fault in its incipient stage thereby reducing the voltage disturbance to the system, minimizing the damage at the fault, and reducing the stress on the circuit breakers ground protection is approaching the importance of becoming the first line of defense. The increased spacing of high-tension open wire lines, and the use of the H cable and the segregated phase installations should greatly increase the preponderance of ground faults and consequently the protective system should be able to recognize such faults and remove them before phase-to-phase action results.

The purpose of this paper has been to indicate briefly the relay practises at the present time and to endeavor to point out what appear to be the necessities of the immediate future.

* * * * *

INTRODUCTION

IN 1919 a paper[2] was presented before the A. I. E. E. giving a very interesting résumé of the relay protective systems up to that date. This was so well received and proved to be of such value that it was felt that a paper of this type presented from time to time would serve as a review and record of modern relay practises. Part II, which appeared in 1922, met this purpose in an excellent manner, and is still a reliable and instructive guide for the protection engineer.[3]

Since the publication of the last paper, several important developments have been made, and it is now felt that the recent improvements warrant a third paper on this subject.

The title of this paper has been changed somewhat from the previous papers to permit the addition of notes on the protective practise for the main items of equipment in a transmission system.

Probably the greatest change in the design of a protective system has been the realization of the importance of shortening the time for removing a fault. With the large quantities of power involved in the present generating and transmission systems, it is very important to disconnect faulty equipment as soon as possible to preserve the system stability, insure continuity of service through other circuits, prevent synchronous apparatus from dropping out of step, minimize the spread of the disturbance to adjacent phases or lines and to remove the fault before much material damage has occurred. This requirement overshadows the former method of purposely introducing time delay so as to reduce the required interrupting capacity of the oil circuit breaker. The modern tendency is to disregard this decrement and to install breakers with a sufficient factor of safety to handle the present and future maximum fault currents, so that full advantage of rapid relay and breaker operation may be utilized to the ultimate.

In conjunction with this minimum operating time, there has been recently a remarkable development of the high-speed breakers. It is now possible to produce commercially an oil circuit breaker with two or three million kv-a. interrupting capacity which will open the circuit in two to eight cycles from the time of the fault. The relay art has kept pace with these developments.

The cost of a relay protective equipment should not be considered as a deciding factor, since it is only a small percentage of the cost of the system being protected, or of the monetary and good will value of the service. Often a reduction of a few tenths of a second in a relay operation, or the installation of "back-up" protection is well worth considerable complexity and cost.

There is also a tendency in the relay art at this time to adopt types and schemes which have inherent selectivity in operation. Under this category may be included impedance relays, all schemes of balanced or differential relays, split conductor relays, and pilot wire relays or equivalents such as the carrier current schemes.

Another feature affecting the relay art is the tendency toward the simplification of the design of transmission

*(Paper prepared in conjunction with H. P. Sleeper, Chairman, O. C. Traver, R. Cordray, L. N. Crichton, E. A. Childerhose, and H. A. McLaughlin, all members of the Relay Subcommittee of the Committee on Protective Devices.)

1. Station Engg. Dept., Edison Electric Illuminating Co. of Boston, Boston, Mass.

2. *Transmission Line Relay Protection*, by H. R. Woodrow, D. W. Roper, O. C. Traver, and P. MacGahan, A. I. E. E. TRANS., Vol. XXXVIII, 1919, p. 795.

3. *Transmission Lines Relay Protection—II*, by E. A. Hester, O. C. Traver, R. N. Conwell, and L. N. Crichton, A. I. E. E. TRANS., Vol. XLI, 1922, p. 670.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

systems. Formerly transmission design had as its sole object the supplying of sufficient load to the stations with a reasonable amount of reserve and diversity. This type of planning frequently imposed severe hardships on the protective schemes. It is now commonly recognized by operating engineers that the design of the transmission and of the relay systems must be considered together. The design of both is, of course, ultimately decided by economics, but as long as the problems are considered mutually, the best protective scheme will invariably result. The importance of this procedure cannot be overemphasized.

In preparing this paper, reference has been made to the various papers presented before the A. I. E. E., to the N. E. L. A. relay handbook, and to data furnished last year by various operating companies to the Relay Subcommittee of the A. I. E. E.

In general, relays and schemes described in the previous papers, and which are still applicable, will not be discussed here in detail, as reference may be made to the preceding papers.

Relay symbols also will not be repeated here, as they have been standardized by the A. I. E. E. and N. E. L. A.

Standards and definitions for relays are now in the hands of a working committee of the Standards Committee of the A. I. E. E., and it is expected that a report will soon be available.

PHASE-TO-PHASE PROTECTION OF TRANSMISSION LINES

Radial Feeders. This heading includes such radial feeders as are independent of each other, have no sources of back-feed, and are not divided into successive sections. In general, the only protection given them is for overcurrent, the relays being instantaneous or with a small time delay, depending on the type of load or service, and on the interrupting capacity of some of the older types of breakers.

Single Line Networks. Feeders having a possible back-feed, or with more than one source of power, and those which are divided into sections, require a more complicated protective scheme, as special consideration must be given to insure that only the element in trouble shall be disconnected, the others being kept in service. As a means of convenience, they may be discussed in the following order:

Selective Timing Between Stations. When there are several stations in succession, it is desirable to trip the breaker closest to the fault, thereby permitting the stations toward the source to remain in service.

Graduated definite time settings will insure that proper selectivity will be obtained between successive stations, independent of the value of fault current. The stations nearer the generator are inherently "back-ups" for the more remote stations.

Discrimination between successive breakers may also be met by setting the remote relays at lower current values than the nearby ones, if the reactance of the line is sufficiently high to cause the fault current to taper off as the distance from the source increases. Usually, however, this differential in current is too small to insure correct discrimination, but this principle combined with the preceding, is of great value, especially for complicated networks.

Probably three-quarters of the present relay applications include a relay which is a combination of the above

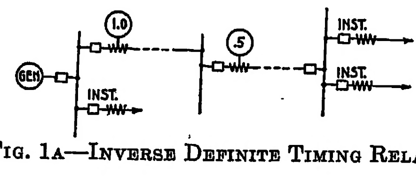

FIG. 1A—INVERSE DEFINITE TIMING RELAYS

features. This is the standard inverse definite time relay whose time of operation decreases as the current increases, until the adjusted minimum time setting is reached. This insures selectivity between stations, rapid tripping on heavy faults, and improved discrimination between feeders on one bus by virtue of the per cent increase on a small capacity feeder being many times that of the larger incoming supply circuits. (Fig. 1A.)

Although the above relay has given, and is giving, a very good account of itself, it is often too slow for present day systems, as the relay next to the generating station must be set longer than the more remote stations, and its timing may reach two or three seconds, which, of course, is far from the few cycles which is possible in the breakers.

One of the most interesting developments in recent years has been the production of the so-called "distance" relay. The impedance type consists of an inverse definite timing element similar to the above, with an added feature which automatically decreases the time setting as the line voltage decreases. Thus with a nearby fault, the heavy current and the lowered voltage both tend to decrease the timing of the relay. Such a

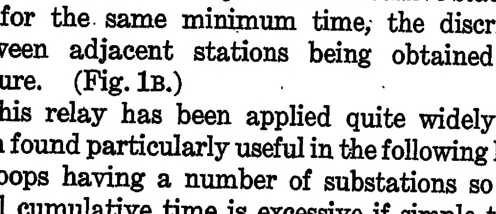

FIG. 1B—IMPEDANCE RELAYS

design permits the relays at the successive stations to be set for the same minimum time, the discrimination between adjacent stations being obtained by this feature. (Fig. 1B.)

This relay has been applied quite widely and has been found particularly useful in the following locations:

Loops having a number of substations so that the total cumulative time is excessive if simple time limit relays should be used.

Systems whose generating stations are frequently cut in or out, and whose connections are changed so often that time limit relays are difficult to adjust.

Interconnected systems which are so closely connected that trouble on one seriously affects the other, thereby requiring that the selectivity on one system should match with the other.

Installations to sectionalize a generating station bus; in this case feeder and bus reactors are used so that the impedance relays can tell when the trouble is on the bus, or when it is on the line side of a reactor.

In order to obtain selectivity between adjacent stations the relay must be adjusted to add the required interval to its minimum time setting, this timing being due to the voltage drop under fault conditions through the line section to the next substation. This means that a fault at the far end of a line section will cause the relay to have a total time setting of 0.7 or 0.8 second, which in certain applications may be too long. A high-resistance fault will materially increase this time setting.

If a breaker should fail to operate, the next nearer station will open at an increased timing. This "back-up" protection is of the utmost importance, but for a short section followed by a long section, this "back-up" timing becomes excessive.

With the present relays, the minimum length of line between stations must be sufficient under minimum short-circuit conditions, to give a voltage drop of approximately 5 per cent of the line voltage. This often prevents their use on short line sections.

Due to the large number of factors to be considered and the accuracy of setting required, it is quite important that the minimum fault currents are fairly accurately known. This may involve considerable calculation and study.

Since the timing is dependent on the voltage applied to the relay, accurate means must be taken to obtain values corresponding to the actual line voltages. The usual method is to install high-tension potential transformers. In cases where this cost is difficult to justify, low-tension potential transformers may be used with compensators which correct for the voltage drops through the power transformer. Such a scheme is quite complicated and may require recalibrating if transformers are added or removed. The use of bushing potential devices on the breaker or power transformer offer an encouraging substitution for high-tension potential transformers.

For systems having a load current relatively large compared to the fault current, the impedance relays may be normally short-circuited, and only brought into service by fault-detector relays during trouble.

One well-known European distance relay is similar to the above except its timing is varied by the line reactance instead of the impedance, thereby tending to eliminate the additional time due to the resistance in the fault.

A new impedance relay is being developed which will have a constant minimum time setting approaching a very few cycles.

Although this new relay has most of the limitations of the standard impedance relay, yet its very high speed for nearly the entire length of line section will offer a solution to many protective problems in connection with interconnected systems, or where stability is a factor. The relay and its use is being described in companion papers.

Directional Relays. Faults beyond a substation produce currents and voltage conditions for the incoming line, the same as for the outgoing feeder in trouble. This would tend to operate both relays; therefore it is necessary to add a device which will prevent the relay on the incoming line from operating. This directional feature should be included on all incoming feeders which have a source of power, these elements being connected to operate only when the fault current is away from the substation bus.

Since a potential is generally used as a base to indicate direction, it is necessary to insure that this potential is always available and will at all times approximately correspond to that of the feeder in trouble. It should be noted that, theoretically, it is possible to have an improper operation for certain classes of faults when the potential transformers are connected to the low-tension side of the station power transformers, but this condition is normally disregarded in practise.

There are two types of directional relays, one using three single-phase over-current relays with one polyphase directional relay, the other having three relays each having a current and a single-phase directional element. The choice of systems depends on local conditions such as power and potential transformer connections, ratio of load and fault currents, and in some cases, the remainder of the relay protective system.

The directional feature may be used in conjunction with any of the over-current or impedance relays mentioned above, the individual considerations being the same as described.

The conventional arrangement of placing the contacts of the directional relay and the over-current relay in series, has several shortcomings. The most serious one is, that while trouble is being cleared by the opening of breakers, there may be a reversal of power flow through a breaker on a good section of line, whose over-current relay has already been closed, so that this breaker will be improperly tripped when its directional contacts swing over to the closed position. Another difficulty is that the current setting must be low because of a small supply of outgoing power, yet the relays may be subjected to a frequent heavy, incoming load which will result in the current contacts' being closed. This removes the time element feature if trouble should occur while such a load condition exists. These troubles have been eliminated by arranging the directional relay so that it renders the over-current relay

inoperative when power is flowing into the station. The over-current time line relays will, therefore, not begin to move until power is flowing away from the bus.

An objection to this arrangement is that it introduces an extra time delay, namely, the time required for the directional relay to operate. This may be avoided by using an additional locking relay, which picks up instantaneously, but when deenergized, drops out with a time which can be adjusted to be the same as the minimum definite time of the over-current relay. (See Fig. 1c.)

Another use for a relay combination which will not

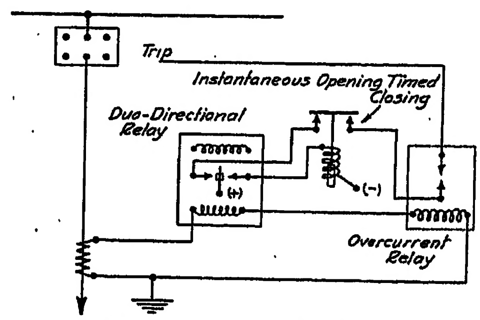

FIG. 1c—TIME CONTROLLED DIRECTIONAL RELAY

start its timing operation until the directional element allows it to do so, is for the "back-up" protection on balanced lines, which are primarily protected by differential relays. In this arrangement, it is usually desirable to delay the start of the "back-up" timing relays until the differential relays have operated, and the flow of power is in the outward direction.

BALANCED OR DIFFERENTIAL SCHEMES

Split Conductor Method. Each phase lead is composed of two conductors operating in parallel and

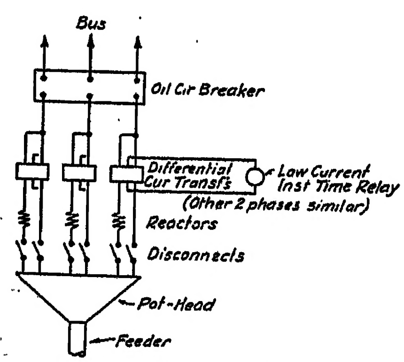

FIG. 2—SPLIT CONDUCTOR

normally carrying approximately equal currents. Most faults will initiate on one of the wires, thereby causing an unbalance in the pair. This differential is determined by means of cross-connected current transformers. The relays can safely be set very fast, and for quite small current. Reactors are inserted in one leg to provide the necessary unbalance when both wires fail. The experience with this protection has been excellent, but the system is decreasing in use, due to the cost and inconvenience of obtaining and stocking the special cable and apparatus. (Fig. 2.)

Pilot Wires. Schemes using pilot wires to balance conditions at one end of a line section against the other end, are very much in use in Europe, but have not received much favor in America, due to the high cost and the technical difficulties involved in the use of pilot wires over the long distances common to our lines.

For short sections of lines or for important tie lines in extensive and complicated networks, pilot wire protection offers the best prospects and their use may increase, unless new relay schemes are developed.

There are many types of pilot wire schemes, some using current and other voltage balancing. In some installations current is circulated through the pilot wires, but the tendency is towards the zero or opposed voltage methods. (Fig. 3.)

Carrier Current. A very ingenious system has been devised which balances the instantaneous polarities of the current waves at the two ends of a line section, by means of carrier current superimposed on the line itself.

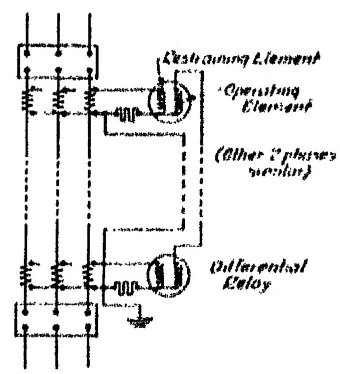

FIG. 3—PILOT WIRES

Under normal conditions, the instantaneous direction of current flow at each end of the transmission line is the same, but at the time of fault, one end generally reverses or else becomes zero. The line current is used to supply plate and grid voltages for three-electrode tube oscillators. Since plate current flows only when the alternating plate voltage is on its positive half-cycle, it is possible to transmit from one end of the line and receive the impulse at the other end, for the one-half cycle durations. Similarly, this is repeated for the other end of the line, which will be transmitting during the other half-cycle duration.

Under these conditions, carrier-current is flowing first from one end of the line to the other, and vice versa, changing every half-cycle. The plate current is smoothed out with capacitors and is used to hold open the contacts of an induction over-current relay by means of a restraining coil.

In order to trip the breaker, it is necessary that there be sufficient over-current flow in the lines to close the over-current relays, and that the instantaneous direction

of current flow be different at the two ends of the line, or that either becomes zero.

It is possible either to operate the tubes continuously, or to have the tubes begin to operate as the over-current approaches the setting of the over-current relay. The over-current relay used is of the induction type, having a time delay of less than 0.1 second.

The reports on the operation of this system have been good.

Parallel Lines

The growth of the use of parallel lines (usually in pairs) has been rapid due to the increased reliability of service and to the relative ease of obtaining selectivity and high speed of the relay protective system.

In general, the schemes used may be divided into the following classifications:

Individual Lines. Each line may be treated individually and equipped with the directional over-current or impedance relays discussed above. The systems involved in this first general method will not be gone into as they are generally well-known, but there are some limitations which should be considered.

If standard directional relays with graded time settings are used on a pair of parallel lines, a fault on one line near the station with the longer time setting, may trip both breakers on the other end of the section, since both will have fault currents of the same value and direction. On the other hand, if the fault occurs near the station with the shorter time setting, both breakers on this end may be tripped, due to the fault current through the good line after the first breaker has opened.

These conditions can usually be taken care of by proper settings, interlocks, the so-called directional controlled relay, or by a combination of these methods.

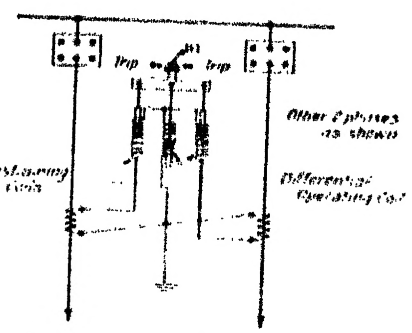

Fig. 4 Parallel Lines Mechanical Unbalancing

These contingencies may not exist, due to the distribution of current in a particular circuit, especially if there is another source of back-feed, but they should be checked carefully.

Directional impedance relays overcome these objections and are operating satisfactorily for installations having any number of lines.

Balanced Current Schemes. The various balanced current schemes have several important advantages, such as fast operation, simplicity of connections, omission of potential transformers, etc., but there are certain limitations which must be considered. Thus they cannot be used on the substation end of a pair of lines if the station has no other source of supply. In this case there would be no unbalance if the fault current is large compared with the load current. On the other hand, if the load current is appreciable, the wrong line may be tripped.

In general, these relays have an operating coil and a restraining coil. The windings are so proportioned that the operating current must exceed the restraining

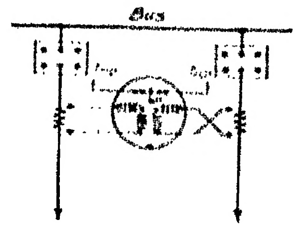

Fig. 5 Parallel Lines Magnetic Balancing

current by 25 per cent before the element will close its contacts. As the restraining current decreases to zero, the operating current decreases to the minimum operating current for which the relay is set.

When applying these types of relays, their individual characteristics should be carefully studied in connection with the characteristics of the system involved, and the operating conditions which will exist. The manufacturer's recommendations regarding connections should be followed, especially with the last type mentioned, as a change in the connection causes a difference in the differential current required to trip.

One of these schemes uses a mechanical balancing relay, as described in the previous 1922 paper. (Fig. 4.) A recent modification of this relay includes a potential restraining coil, thereby automatically reducing the required operating differential current, if the fault is nearby, and the line voltage is affected. This relay is being discussed in a companion paper.

A second type has two induction elements, each having an operating and a restraining coil. The action is similar to the above mechanical or plunger type.

In another type the currents from the two lines are connected to two sets of coils on the same magnetic circuit, the balancing being accomplished magnetically. The relay is provided with double-throw contacts and an unbalance causes the relay disk to operate and trip the breaker carrying the greater current. (Fig. 5.)

On solidly grounded systems, phase protection of the above types would also clear ground faults. However, there usually is an advantage in using ground protection of the same balanced types. In general, the phase relays must be set high in current to avoid trouble due to switching. The ground relays are not subject to this limitation, and can be given a low current setting.

Since the majority of faults involve ground the over-all sensitivity is increased.

Cross-Connected Directional Schemes. The simplest and most general arrangement consists of two sets of directional over-current relays with their current coils connected in series across the cross-connected current transformers of the two lines. The potential connections to the relays are reversed so that only the trip cir-

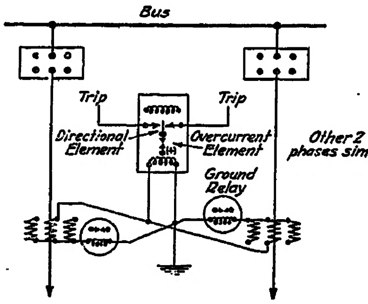

FIG. 6—PARALLEL LINES—DUO-DIRECTIONAL RELAYS

cuit of the breaker carrying the greater current will be closed by the unbalanced current.

The same results can be obtained by using one set of duo-directional over-current relays or by means of one set of over-current relays and two uni- or one duo-directional relay. (Fig. 6.)

If the time and current settings will allow, the same relay may be used for single line operation, although it is generally necessary to use additional relays for this purpose. It is also necessary to add other relays for

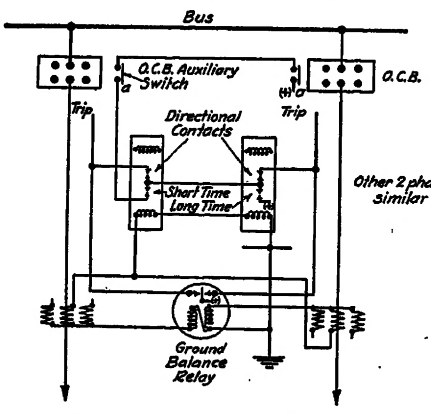

FIG. 7—PARALLEL LINES—CROSS-CONNECTED DIRECTIONAL RELAYS

simultaneous faults on the two lines, and for through faults.

A second method sometimes known as the short and long time schemes used two sets of directional relays, but the over-current and directional contacts are interconnected so that each directional contact is associated with an individual line, while the over-current contacts are common.

One of these current elements has a short time setting and the other a long time setting. The first is arranged to be cut out by auxiliary switches on the circuit breakers when either line is open, thus leaving the long time setting in service for single line operation. (Fig. 7.)

This scheme also requires additional relays for simultaneous and bus faults.

A scheme which gives short time protection for double-line operation, and long time protection for single-line operation, and which also offers protection against simultaneous line and through faults has recently been developed and appears to meet most situations.

The current transformers of the two lines are cross-connected through an auto-current transformer, across which is an over-current relay. The directional relay is connected to the midpoint of this auto-transformer.

The "back-up" protection for through faults has the same pick-up, whether one line or both lines are in service. This will readily be understood if it is kept in mind that the auto transformer has a high impedance compared to the relay. Thus for equal current in each line, the total circulating current passes through the

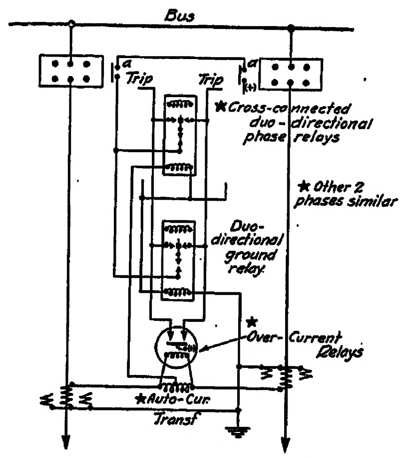

FIG. 8—PARALLEL LINES—CROSS-CONNECTED RELAYS WITH AUTO-CURRENT-TRANSFORMER

over-current relay connected across the auto-transformer. If the same total current is passing through one line, the secondary current will divide equally through the two halves of the auto-transformer, and only one-half passes through the relay. Thus the current through the relay is the same for a given primary current, whether it is passing through one line or both. (Fig. 8.)

In all these balance schemes, careful thought and study should be given to the matter of back-up protection, for simultaneous faults on both lines and for bus faults, not as a duplicate system of protection, but as additional protection to take care of special conditions which may arise at any time.

These schemes should be carefully studied as to the effect of switching in or out the second of a pair of balanced lines, since it is impossible to close or open both ends simultaneously. Incorrect relay operations may result unless the current settings are higher than any normal load or surge carried on one line, or unless special interlocks are included.

The comments given in connection with ground protection by the use of current differential schemes, apply equally well to the balanced directional schemes.

Occasionally balanced lines are connected to different sections of a bus, which may operate with the sectionalizing switch open. In this case some provision must be made for cutting the balanced protection out of service, either manually or by auxiliary switches on the sectionalizing breaker.

In applying differential protection to more than two parallel lines, it is now considered better practise to protect them by pairs. Thus in the case of three lines, Nos. 1 and 2, 2 and 3, and 3 and 1, would be balanced using the regular schemes for pairs of lines.

In general, balanced line schemes are giving satisfaction, and their use is increasing.

Ground Protection

Present-day transmission systems are generally grounded at one or more points. Experience has shown that most faults on these systems start as a flashover or failure to ground; therefore, on a grounded system, the flow of ground current is a positive sign of trouble. Because of this, ground fault protection is of extreme importance, and is gradually becoming recognized as a front line of defense against damage caused by fault currents.

Zero phase-sequence component currents flow only during ground faults. They may readily be isolated from the positive and negative phase-sequence components by means of a simple network. Three star-connected current transformers will permit only the zero phase-sequence component currents to flow through their common or residual circuit. This connection is in common use and the zero phase-sequence or ground relays are connected in this residual circuit.

Since ground currents are not present during normal operation, no consideration need be given to load currents when considering the zero phase-sequence relays. They may be set to operate on very small currents so that in many cases they will isolate the faulty section or piece of apparatus while the trouble is still in an incipient stage.

Solidly Grounded Systems. Frequently the ground fault currents exceed the load values and the line phase-to-phase relays will also give ground protection. However, ground fault currents decrease in value, as the point of fault moves away from the grounded source much more rapidly than phase-to-phase fault currents, and on long lines it is necessary to use zero phase-sequence relays to give protection against ground faults remote from the relay.

Residual Current Protection. Over-current relays used as ground relays may be installed in the residual circuits of current transformers. This system is applicable to radial or stub-end feeders. Selectivity is obtained in the same manner as over-current phase-to-phase protection on similar systems. (Fig. 6.)

Current Differential Protection. Current differential relays may be connected in the residual circuits of the current transformers on parallel feeders. The application is the same as the phase current differential relays on parallel feeders, as previously explained. (Fig. 7.) Quite frequently parallel feeders to a substation have taps to supply customer loads, and under these circumstances, it is not always practical to obtain phase-to-phase protection by means of differential relays. The flow of ground current, however, in either feeder indicates trouble on that feeder, and advantage may be taken of this fact and current differential ground relays installed on the feeder.

Directional Residual Current. Directional ground protection may be obtained with directional over-current relays potential element being connected in one corner of the secondary delta of three star-delta connected potential transformers.

Directional over-current ground protection may also be obtained by use of a relay whose directional element is polarized by a current transformer in the neutral of the main power transformers. Ground fault currents

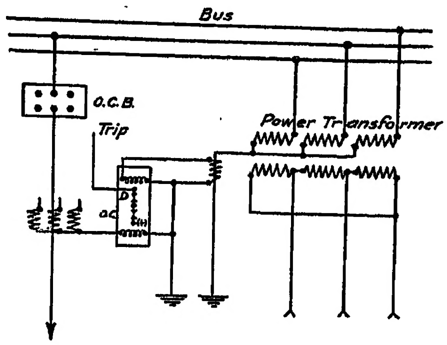

Fig. 9a—Directional Ground Relay

always flow in the same direction in this ground connection, and advantage is taken of this fact. This method eliminates high-tension potential transformers. (Fig. 9a.)

Power Type Residual Relays. Protection against ground faults may be obtained by using a power type relay with its potential element connected in the secondary delta of star-delta potential transformers and the current coil in the residual circuit of the current transformers. It has a theoretical advantage of quick operation for nearby faults, but quite frequently its use is limited because the voltages do not unbalance sufficiently to give enough residual voltage to operate the relay. When this relay is used at a station which is not a point of grounding, special care should be exercised with the connection to insure that resonance shall not occur between the inductance of the potential transformers and the capacity of the line, if the protected section of the line should be left grounded only through the potential transformers by the opening of a circuit breaker. Such an occurrence might displace the electric neutral of the lines to such an extent that

destructive potentials would appear on the lines. (Fig. 9B.)

A power relay with its current coil operated by the residual current of the current transformers and its other coil in the ground connection of the power transformer, is directional, quite sensitive, and has the desired inverse time characteristics. (Fig. 9C.)

Balanced Directional Residual Current Relays. Directional over-current relays may be balanced to give protection against ground faults in manners similar to those for protection against phase-to-phase faults,

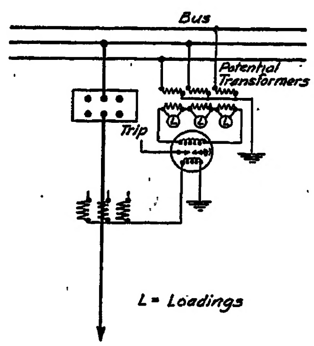

FIG. 9B—POWER DIRECTIONAL GROUND RELAYS

except that potential must be supplied as described above. (Fig. 8.)

Distance Relays. Various types of distance relays used for phase-to-phase protection may be connected to the current transformer residuals and star-star connected potential transformers. Three relays are required per line for complete ground protection. The

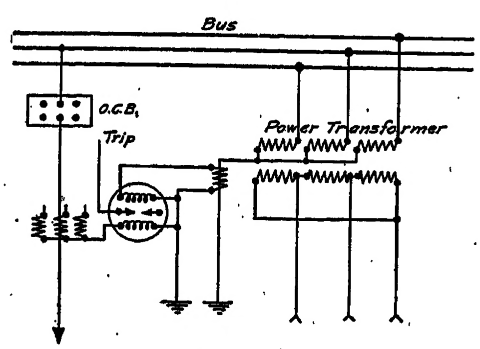

FIG. 9C—POWER GROUND RELAY

wiring is complicated and operation is sluggish for small fault currents.

Pilot Wire Protection. Any of the split conductor or pilot wire schemes inherently give ground protection, though for small ground fault currents, it may be preferable to add a sensitive relay in the current transformer neutral circuit.

Isolated Neutral or Delta Connected Systems. A ground on one phase is not followed by a power current, and in itself is not particularly dangerous. It, however, increases the potential strain on the two ungrounded phases on all parts of the system and, if not removed, may develop into a phase-to-phase short-circuit. An arcing ground may set up surges which cause dangerous voltages to appear.

Voltage Relay. Overvoltage relays connected in the corner of the delta of three star-delta connected potential transformers may be used to indicate these unbalanced voltage conditions. Under normal operating conditions there is no current flowing in the delta, and the relay potential is zero. In case of a ground on the line, this voltage becomes quite large. Harmonics and large charging currents may seriously upset such a scheme, but their effect can usually be eliminated by adding a load across the secondary of each potential transformer. This arrangement only indicates a ground fault, but does not locate it. It is applicable, then, for tripping breakers only on single feeders, or a series of radial feeders, where selective timing may be used. (Fig. 10.)

Charging Currents. When one phase of the system is grounded, there immediately appears on all conductors a charging current to ground. On a large system, this charging current is of sufficient magnitude

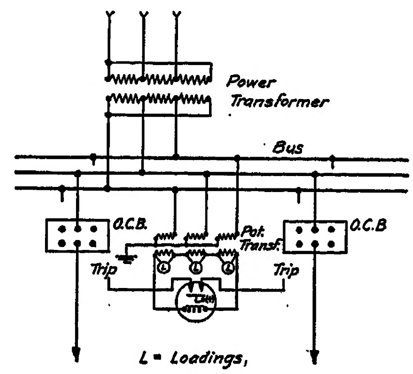

FIG. 10—VOLTAGE GROUND RELAY

to operate relays. It increases in magnitude as the point of fault is approached. It appears in the residual circuit of three star-connected current transformers, and may be used to operate directional over-current relays. The potential for the relays is usually taken from the corner of star-delta connected potential transformers as described above, if high-tension potential transformers are present, but potential may be supplied from the low tension side of the power transformers if necessary.

High-Impedance Grounded Systems. The ground protection of high-voltage systems using a relatively high-impedance ground presents a difficult relay problem. It is particularly pertinent that such faults be relieved, since dynamic current actually flows to ground and not as in the case of isolated systems only a charging current which passes to ground. Moreover, high voltages may appear on the system during such a ground fault, and simultaneous faults may be avoided if the ground fault is relieved quickly.

The ground relay system must obviously operate on a

small amount of current to ground, thus requiring sensitive relays.

Current transformer circuits connected to such relays must be accurately balanced, as an improper unbalanced secondary loading will pass load current through the sensitive ground relays and operate them incorrectly. Ordinarily the relay volt-ampere burden is high and care must be taken that the current transformers are not over-burdened. The particular problem giving directional operation to such relays, and the use of inside delta potential has been found most satisfactory for this, since the relays operate when so connected with a power-factor close to unity.

Another problem of such relays is to take care of simultaneous faults on opposite phases on separate parts of the system. Power-factor conditions over an extreme range may be presented to the relays, and it is impossible for the relays to detect current operating conditions from incorrect, under such circumstances, at certain locations on the system. The most practical solution for such a condition has been to lock out the ground relays during simultaneous faults and allow phase relays to function to relieve the disturbance.

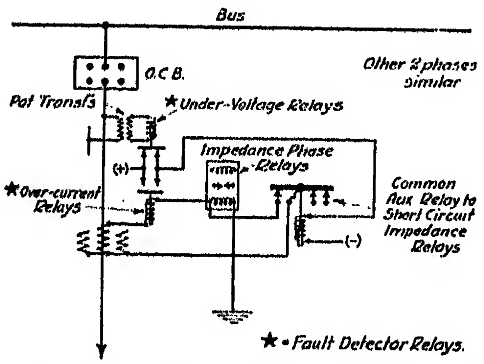

FIG. 11—IMPEDANCE RELAYS FOR SMALL FAULT CURRENTS

This is accomplished by utilizing the short-circuit current which flows in the neutrals under these conditions to operate lockout relays which render the directional ground relays non-operative.

If the ground current is sufficient to produce a difference in voltage drop between stations, impedance ground relays may be used which are introduced by fault detector relays during a disturbance. These fault detectors are usually a combination of over-current and undervoltage relays. (Fig. 11.)

APPARATUS PROTECTION

Bus Sections. In the past it has not been the general practise to provide relay protection for the main bus sections in a station, as bus faults are seldom experienced, due to the method of construction and design of the bus installation. In recent years, however, there is a tendency to install some type of protection due to the large amounts of connected kv-a. capacity, especially since most of the protective schemes for the rest of the system exclude the bus.

Balanced protection of each phase where all the current transformers (using auto-balance transformers if of unequal ratio) are connected together to an over-current or differential relay, is commonly used and offers accurate and fast protection. It has the disadvantages of tripping the bus in case any of these current connections fail, or if any of the current transformer ratio curves are not similar on heavy external short circuits.

A modification of the above connects only the secondary neutrals together. This is safer in many ways,

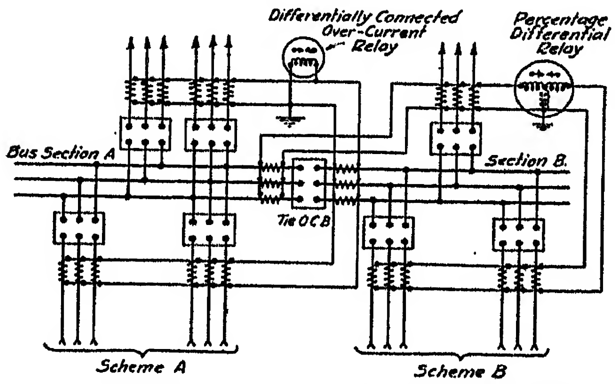

FIG. 12A—GROUND PROTECTION NEUTRAL DIFFERENTIAL

but it only gives protection against ground faults. This protection is sometimes considered all that is necessary, as most faults occur initially to ground, especially in isolated phase and outdoor installations. (Fig. 12A.)

Over-current protection, especially if combined with undervoltage relays, may sometimes be applied. The impedance relay may safely be used for bus installations having feeder reactors.

Several installations have been made using sections of

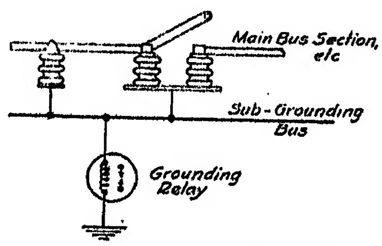

FIG. 12B—GROUND PROTECTION

ground bus connected to insulator bases, circuit breaker tanks, supports, etc., with relays inserted in the ground connections from these busses. The action is rapid and satisfactory as long as the ground bus and structure are well insulated from the building steel. (Fig. 12B.)

Power Transformers. Since the input and output of the transformers are very nearly equal, it is a relatively simple matter to balance one against the other and consider any unbalance to be due to a fault within the transformer. Care must be taken that these balancing or differential relays are not too sensitive, as there is

some unbalance due to the variation in ratios of the current transformers on the two sides of the transformer. This is particularly true during an external short-circuit or due to the inrush of magnetizing current when the transformer is first energized.

There are now available current differential relays which operate on the percentage of the unbalanced current with respect to the load current, instead of on a fixed value of unbalance. Such relays will detect a minor fault at normal loads, yet will not operate improperly during an external short circuit.

In applying either type of relay, it is necessary to select currents which are in phase and which are approximately equal or are within the limits of the relay setting. This equalizing of currents, if necessary, may be accomplished by auto-current transformers. For power transformers with tap changing under load equipment, if differentially connected over-current relays are used, it is necessary to provide a corresponding tap changing switch for the auto-current transformer.

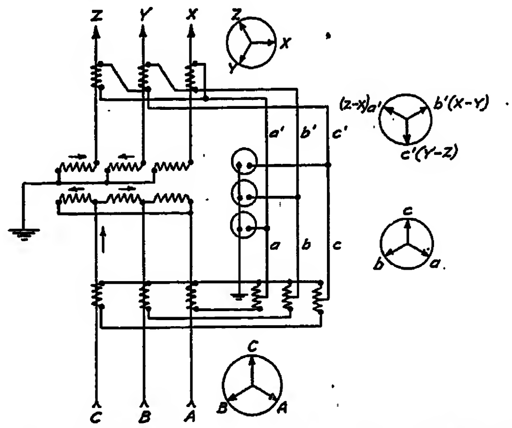

FIG. 13—TWO-WINDING TRANSFORMER DIFFERENTIAL PROTECTION

The new percentage differential type of relay, however, usually permits sufficient unbalance to allow the omission of the auto-balance transformer.

Overload protection is usually included as a back-up to the differential protection and as a back-up feature for the rest of the system.

Two-Winding Transformers. Single-phase or three-phase transformers which are delta-delta or star-star connected offer no complexity as the corresponding phase leads are balanced together. A delta-star combination, however, requires the current transformer on one of the phases of the delta side to be balanced with the two current transformers of the star winding. (Fig. 13.) A Scott connected transformer should be treated in a similar manner, that is, the path or paths of one phase of the load current should be traced through the various windings and the current transformers selected accordingly.

Three-Winding Transformers. The same principles as above apply, with the added requirement that the primary winding should be balanced against both of the two secondaries. (Fig. 14.) If the system connections require it, it may be necessary to balance the two secondaries against each other.

Regulating Transformer. A regulating transformer used as tap-changing-under-load equipment for a power transformer performs in a similar manner to an induction voltage regulator. Protection is obtained by

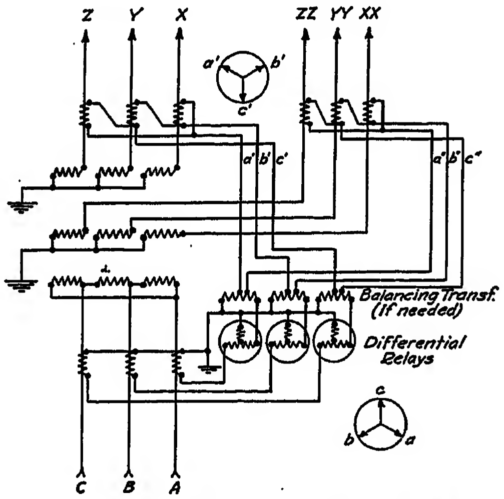

FIG. 14—THREE-WINDING TRANSFORMER

balancing the current of the exciting or voltage winding against that of the series or current winding when the equipment is on either the maximum buck or boost position. An external fault will increase both currents several times, but the ratio remains nearly constant. A ground fault or a fault within the unit which increases the current of the exciting winding will operate

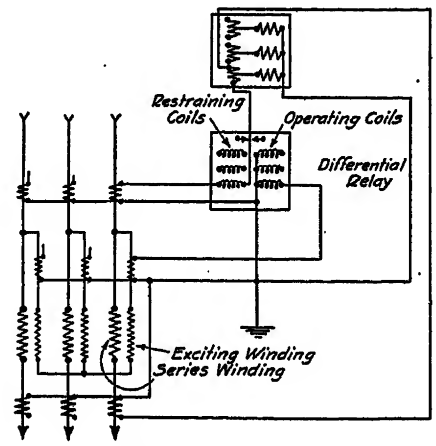

FIG. 15—DIFFERENTIAL PROTECTION REGULATING TRANSFORMER

the relay. The setting must be sufficiently high to prevent operation on the initial heavy inrush of magnetizing current. For the zero position where there is no current in the exciting winding, an additional percentage differential relay is necessary. (Fig. 15.)

Generators. Generators are normally not protected against overload, as it is desirable to maintain service

as long as possible and to permit the fault to be isolated by the circuit breakers of the line in trouble. On the other hand, the value and importance of the generator necessitates that it be removed immediately in case of internal trouble. This is best met by providing some type of balanced or differential protection.

The usual method has been to balance the current transformers in the main leads against those in the neutral. An internal fault would cause an unbalance

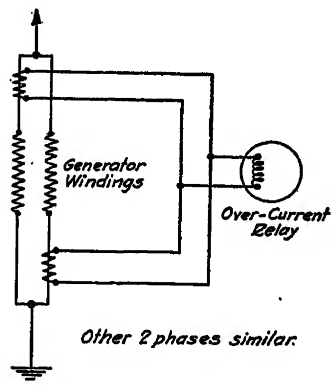

Fig. 16A—Parallel-Winding Generator Differential Protection

and the differential relays would operate. Since the current transformers may all have similar ratio characteristics, these relays may have a very sensitive setting. (Fig. 16A.)

The percentage differential relay can be set even closer as its action is proportional to the load current, and the relay will be restrained from opening on a

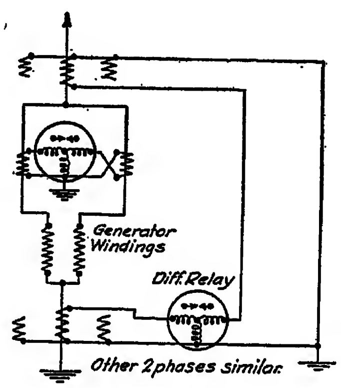

Fig. 16B—Parallel-Winding Generator Differential Relays

through short-circuit, even with some unbalance of the current transformers. (Fig. 16B.)

Parallel winding generators may have balanced protection between the windings, in addition to the over-all differential protection, or may have these two functions combined into one set of relays. (Fig. 16B.) Another scheme uses a current transformer and relay connected between the mid-points of the two windings. These relays operate on grounds and on faults between turns or phases, but the scheme may be difficult to apply, as the mid-points are often difficult to locate. (Fig. 17.)

Automatic shut down of the generator should include tripping the main breakers, neutral breaker, field breaker, throttle, ventilating system, and fire protective scheme as applicable.

Generators, especially water wheel units, may develop dangerous overvoltages when the load is suddenly dropped. This condition may be prevented by overvoltage relays which reduce or trip the field or shut down the set.

Conclusions

We have endeavored in this paper to point out that the trend of the relay art at this time is toward the use of relays which operate in much shorter times than heretofore practised. It is believed that the use of relays which may be called high speed, operating in a very few cycles, will hereafter supplant many installations heretofore protected by relays operating with a time delay up to an accepted maximum of two seconds. Time element relays will, of course, still find many applications such as the protection of radial feeds,

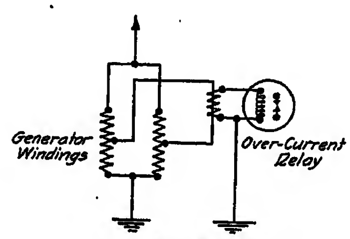

Fig. 17—Parallel Winding Generator Mid-Point Protective Scheme

small machines, back-up protection of lines and apparatus, etc.

One of the greatest needs of the protection engineer at this time is that of improved types of ground relay protection. This requirement will become increasingly apparent as time progresses due to the changing character of power system transmission. Today the base transmission of a system consists of lines or cables operating usually at voltages between 66,000 and 220,000 volts. There is a secondary step in the transmission system consisting of a network of lines and substations operating at voltages of between 13,000 and 33,000 volts. The power is finally transmitted to the customer at voltages of 4000 to 6600, where a local reduction in voltage may occur. The present trend in transmission system design seems to indicate that some of these intermediate steps will soon disappear. Hence the system of tomorrow may consist of only the high-tension base lines and one secondary high-voltage network bus at the customer's voltage only. Such a system could be relayed almost entirely by means of secondary network switches on the customer's end, and ground relays only at the service end. All recent new developments have been along the line of phase pro-

tection. Ground relays are needed that are instantaneous in operation and inherently selective. The fundamental advantages of ground relaying are detection of the fault in the incipient stage, reduction in voltage disturbance to the system, minimizing of damage at fault, and reduced stress on circuit breakers. The increased spacing of high-tension open wire lines and the use of type H cable should greatly increase the preponderance on ground faults and consequently the protective relays should be able to recognize such faults and remove them before phase-to-phase action results. The importance of this is paramount.

Another factor which demonstrates the necessity for improved ground relay protection is the advent of current limiting devices in system neutrals. This practise has a limited application in this country at the present time, but the effects of its use are receiving favorable attention, and this fact should not be over-looked by manufacturers of protective equipment. All of the desirable effects of single-phase faults versus phase-to-phase faults are enhanced by the use of impedances in system neutrals, and many of the objections to such installations have either been removed or are now recognized as being non-existent. It is, therefore, quite possible that systems in the future will limit ground currents in the necessity of system stability, reduction of system disturbances, minimizing of damage, etc., and this will require the use of relays which can detect such faults and operate quickly to remove them.

A further factor which has recently stressed the importance of improved ground relay protection, is the absolute necessity of avoiding three-phase faults on interconnection tie lines. It is frequently the case that such a fault which exists longer than a very few cycles, almost less than the time of opening of the fastest designed breaker at this time, is sure to result in instability. However, practically all faults on such lines start as single-phase or two-phase-to-ground faults, and if they are removed as such within a short time, they will not produce instability. It would therefore appear that ground relays which can be made to operate at all times in a very few cycles would be a distinct contribution to the stability of interconnected systems.

Therefore it seems that the field of improved ground relay protection is one that offers further room for improvement. Much has been done along this line recently, and one of the papers presented at this time demonstrates some excellent work done by one of the operating companies. With the cooperation of the manufacturing companies, the improvement of ground relays should present no serious defects, and it is hoped that the proper attention will be given to this phase of the situation.

The need of accurate operating data on the performance of relays has long been recognized. Such records have, of course, been kept individually by most operating companies, but there has been a lack of uniformity in the methods of doing so, particularly as no common base of comparison had been established. Some excellent work in this direction was done by the Southeastern Division of the Electrical Apparatus Committee, N. E. L. A., under the chairmanship of Mr. E. E. George and published as a serial report in April 1929. It is hoped that all operating companies will be guided by the principles established by that committee, so that comparative records may be used in the future between different companies on relay performance.

The purpose of this paper has been to present standard practise in relay protection at the moment, and to endeavor to point out what appeared to be the necessities of the immediate future. It is the hope of this committee that the practise of presenting such a paper every few years will be continued.

Discussion

W. H. Colburn: One of the needs in relays or relay protective systems—is something which will anticipate the fault and clear it before it occurs. The nearest to anything of this kind is the split-conductor scheme mentioned in Mr. Edson's paper. This particular scheme and its corresponding split-conductor protection schemes were thoroughly covered in a paper by Mr. W. H. Cole of The Edison Electric Illuminating Co. of Boston in 1918, on record in the TRANSACTIONS of that year, but so far is applicable to cable protection only. Operating experience as indicated in that paper and extended during the past 12 years shows that this system usually clears the cable fault in its incipient stages without system disturbance and frequently with so little damage to the cable that the fault is not readily discoverable. Originally, as mentioned in that paper, the cable was put back into service over an extended period before failure reoccurred, but since operating experience shows that operation of this protective system almost certainly indicates a fault, current practise calls for examination and tests of a cable upon which such relay operation occurs to locate the fault.

In spite of its obvious advantages in cable protection this system is not being extended for the reasons stated by Mr. Edson and for two additional reasons. The first and more important of these is the limitation in cable size and therefore power transmitted by the split-conductor construction, and the second is the limitation of the protection to the line itself, whereas some other schemes provide some desirable bus or station protection as well.

H. H. Spencer: In the balanced current schemes discussed by Mr. Edson it should be pointed out that the usual schemes involve opening the trip of the balanced current relays when a line is returned to service after an interruption; otherwise, upon reclosing the first breaker, the corresponding breaker of the line which remained in service would immediately open. The new balanced current relay presented by Messrs. Traver and Kennedy has a voltage restraining coil which completely avoids this difficulty. Staged tests have been made on our system with this relay and it appears to be highly satisfactory both from the point of view of sensitivity and from the point of view of voltage restraint.

R. E. Hellmund: The merits of circuit interruption at various time intervals of from one-half to several cycles and the complications justifiable in order to accomplish such results have been discussed. In this connection it may be of interest to know that the commercial demand for such short periods as one-half to one cycle first originated for reasons outside of the power system proper. In single-phase railway systems short circuits or grounds on the trolley wire lasting several cycles caused considerable trouble in telephone systems, resulting in the so-called "acoustic shock" to telephone operators. It was for the

purpose of eliminating this condition that the first real high-speed a-c. circuit breaker and relay systems were developed. The use of these was subsequently found to have various advantages for the power system proper, among which may be mentioned less contamination of the oil in the breakers, and greater system reliability.

W. W. Edson: It is quite evident from the discussions on this paper as well as on the others of this group that the tendency is towards high speed relay operation with selectivity obtained by means of some type of balancing rather than by timing or current selection. Ground protection is also being emphasized.

This rapid growth of the relay art will require numerous relays to be developed and it is very necessary that the manufacturers use care in the mechanical design of such relays.

A relay may be theoretically and electrically correct but an otherwise satisfactory protective system may be thrown into disfavor if the relay fails from some mechanical reason.

From the standpoint of the relay application engineer it appears that more standardization is required in vector representations, in relay testing and records, and in data for current transformers under short circuit conditions.

There are several special situations which are not being satisfactorily met at the present time, one being the protection of parallel lines having bus sectionalizing breakers at the stations or having taps out on the lines between stations.

The writers of this paper wish to take this opportunity to thank the many engineers who contributed data and information used in its preparation.

Modern Requirements for Protective Relays on Important System Interconnections

BY O. C. TRAVER[1] and L. F. KENNEDY[1]
Member, A. I. E. E. Non-member

INTRODUCTORY

THE usual methods of relaying are becoming inadequate for tie line application. The need for limiting the duration of faults on lines of major importance is unquestioned. The possibility of maintaining stability by quicker operation of protective equipment is well recognized. These considerations have resulted in the development of the high-speed relays and oil circuit breakers as steps in the over-all reduction of short-circuit duration.

Besides limiting the duration of short circuits, it is frequently necessary that the protective equipment function correctly at current values below rated load. On some important interconnections, the range in capacity is such that the minimum short-circuit current is but a fraction of the full load value. It is a requisite, therefore, that the new protective relay types and methods should give rapid, selective action, even at low current values.

It is obvious that the use of cumulative or graded settings will not produce the desired results. Preferably, therefore, the relay equipment should make no attempt to operate except when a fault occurs on the circuit protected or as back-up for disorders in a contiguous line. Furthermore, excepting where the through current is limited chiefly by the impedance of the protected line alone, its absolute magnitude is of little value in determining where a fault exists.

COMPARISON—THE MODERN FOUNDATION

Time having been excluded in the concept of our problems, and current magnitude, or any other single quantity, being too variable to be trustworthy, an immediate comparison of two or more electrical quantities is needed, as a prompt means of discriminating between good and bad. These comparisons may be listed as:

Series Balance......	Comparison of currents at the two ends of a circuit.
Parallel Balance....	Comparison of currents at one end of two parallel circuits.
Balance of Dissimilar Quantities......	*e. g.* current and voltage.

The speed of operation of the directional relays is of unusual importance. They must be fast under all expected voltage and phase angle conditions. A tardy relay may impair otherwise excellent protection.

Though quick action of the relay nearest the fault is a highly desirable feature, it does not necessarily rid the system of the disturbance. The opposite end is sometimes obliged to wait and thereby double the time to completely clear. The various means dealt with in this paper range from about 60 per cent to 100 per cent of effective simultaneous and complete isolation.

SERIES BALANCE

The series balance method gives a comparison of the relative magnitude of current values at two points in the same circuit. It is the best method of obtaining selective action. This is the familiar differential protection, in which an instantaneous comparison is easily made between currents, normally equal, at two points reasonably close to each other. A fault is indicated by an inequality between the two current values. For line protection, such methods involve the use of pilot wires with their attendant expense and technical problems, in proportion to their length. Quick action is secured with simultaneous tripping of both ends of the line, for faults over its entire length.

Related to the foregoing is the carrier current pilot protective system which provides a comparison of relative direction of the currents at the two ends of a line. The breakers at both ends of the line can be simultaneously tripped in 0.1 second or less. For a description of this method, see paper by Mr. A. S. Fitzgerald.[2]

PARALLEL BALANCE

A comparison between currents in two lines which normally bear a definite relation, constitutes a parallel balance.

Split conductor cables fall in this class. Although with them excellent results might be obtained, nevertheless on account of their first cost and more difficult installation and maintenance, they have not found favor on American systems. On the other hand, balancing the currents in pairs of completely equipped lines has become a general practise.

On account of the simplicity, reliability, and speed of this equipment, two similar parallel lines should be protected by balanced relays which will operate to trip one line when its current is a certain percentage above that in the other line. The percentage unbalance is chosen high enough to prevent false operation on small differences, such as may be due to variation in current transformer or transmission line characteristics, unequal mutual inductance, and similar causes. The usually

1. General Electric Company, Philadelphia, Pa.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

2. *A Carrier Current Pilot System of Transmission Line Protection,* A. I. E. E. Quarterly TRANS., Vol. 47, Jan. 1928, p. 22.

accepted value is 25 per cent unbalance on outgoing lines.

For faults close to one end of a pair of parallel lines, the current will flow in opposite directions in the two circuits. Since the direction of current flow in two parallel lines is always the same, unless one of them is at fault, it is permissible to operate on a 10 per cent unbalance when the currents are in opposite directions. Such a characteristic makes for wider application of the

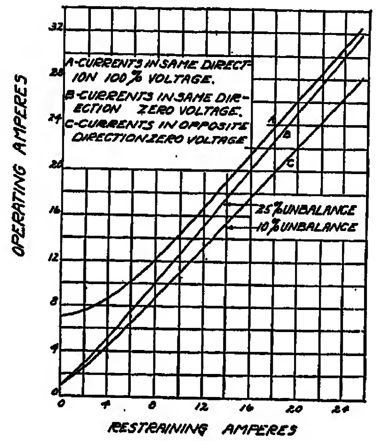

FIG. 1—OPERATING CHARACTERISTICS OF BALANCED CURRENT RELAY USING VOLTAGE RESTRAINT

parallel balance methods. In cases where the generating capacity at the end nearest the fault is very low and where there may not be 25 per cent unbalance, with relays operating in the order of one cycle it is possible to obtain action on current fed from synchronous condensers or induction motors. This combination

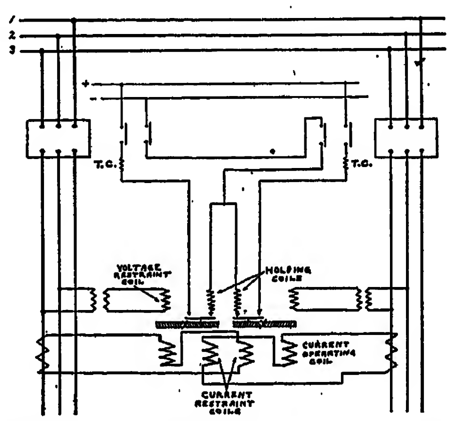

FIG. 2—SCHEMATIC CONNECTIONS FOR BALANCED CURRENT RELAY USING VOLTAGE RESTRAINT

makes balanced current relays almost universally applicable for parallel trunk lines.

Balanced relays should have a straight line percentage characteristic at the higher current values, as shown in Fig. 1. In order to cover the entire range, including low-current faults, it is necessary that the curve continue on down below the normal load. Such a curve with a minimum operating point of 1 ampere is shown in Fig. 1, Curve B.

Where balanced relays are used, they are prevented from tripping the second line after one opens, by means of auxiliary switches on the breakers. With the characteristic referred to above, however, the relay would be ready to trip the line carrying load if an attempt were made to close the associated circuit. To prevent this, a voltage restraining feature is added to the current balance relay, modifying its characteristic at 100 per cent voltage, as shown on Fig. 1, Curve A. This novel feature adds an impedance factor and normally raises the minimum operating point above full load, thereby permitting switching in the open line without special operating requirements. Under short-circuit conditions, a family of curves between A and B is obtained, Curve B being the zero voltage characteristic and A the full voltage characteristic.

Fig. 1, Curve C shows the effect of reversing current in one line, automatically reducing to the 10 per cent unbalance characteristic previously discussed.

This balanced current relay is immediately discriminating, without cascading over an average of at least 80

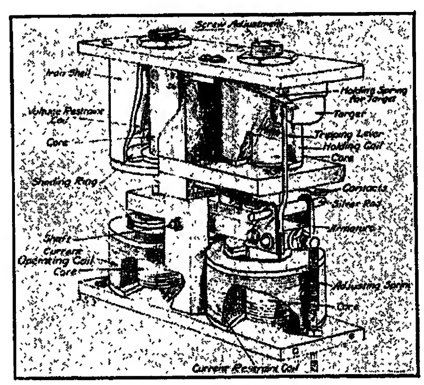

FIG. 3—UNIT OF BALANCED CURRENT RELAY

per cent of the length of the lines. In this regard it occupies the place next to the 100 per cent pilot wire schemes.

The schematic connections of this relay for one phase are shown in Fig. 2. The relay is composed of two units each with its separate circuit-closing contacts for opening one line. Each unit has current operating and restraining coils interconnected, as shown. The voltage restraining coils may be energized from potential transformers associated with the phase which supplies the current coils.

The construction of one unit of the relay is illustrated in Fig. 3, and the complete relay in Fig. 4. Small travel and relatively large forces are used to obtain fast operating time with assurance against false operation from shock or vibration. The current cores and voltage restraining cores are shaded to quiet the operation of the relay under normal conditions and to make it less sensitive to surges.

A holding coil is provided as shown in Fig. 3. This coil seals the contacts closed until the breaker has

opened. The trip circuit is interrupted to both breakers by auxiliary contacts on either breaker, in accordance with long established practise.

A time characteristic, Fig. 5, shows the extremely low values obtained. It is to be noted that at 20 amperes the time is 0.004 second and, in general, is less than 0.016 second (1 cycle on a 60-cycle basis).

In the application of these to two parallel lines, four

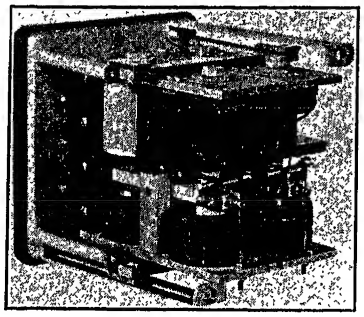

FIG. 4—BALANCED CURRENT RELAY

relays are used, one in each phase, and one in the residual circuit for ground faults. Usually the residual relay will not require the voltage restraining feature.

COMPARISON OF DISSIMILAR QUANTITIES

In any circuit there is a distinct difference in the relative values of current and voltage between load and fault conditions. A relay operating on the ratio of these quantities is, therefore, valuable in indicating the occurrence and location of a fault. The ratio between voltage and current is impedance, and impedance, neglecting the fault component, is a measure of distance.

On any transmission line section the impedance is known and if a relay having an ohmic pick-up is set at a lower value than that of the line its operation will result only in case the section considered is at fault. Such an arrangement needs very little time delay and,

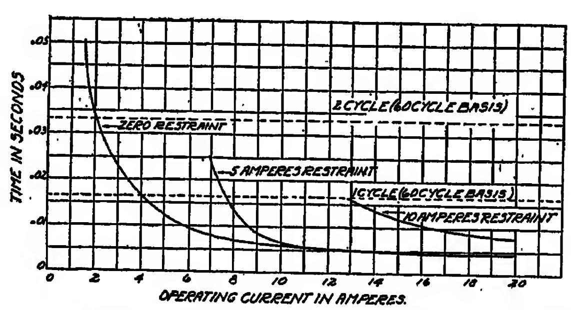

FIG. 5—TIME-CURRENT CURVES OF BALANCED CURRENT RELAY

therefore, approximates the methods which employ a comparison of currents in parallel circuits.

Since it is not practical to set a relay with an impedance pick-up to cover 100 per cent of a given section, it is necessary to provide some means of protection for the far end of the section as well as the bus to which it connects. This protection can be provided by a second similar impedance unit, operating at a higher ohmic value and giving the desired time delay.[3]

An efficient type of protection using an ohmic relay is indicated on Fig. 6. This "step characteristic" protects Line *A* in the minimum time up to about 80 per cent of its length. At this point, time is introduced for the protection of the last 20 per cent of the line and the bus, overlapping well into the next line. The relay on Line *B* would have a similar characteristic. Provision can also be made to give back-up proteciton at *A*

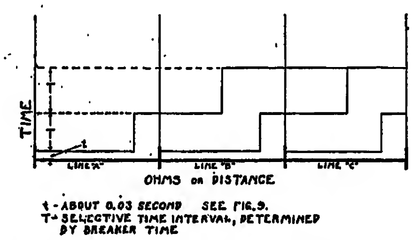

FIG. 6—STEPPED TIME CHARACTERISTICS FOR DISTANCE RELAY

for faults in Line *B*, in case of failure of its circuit breaker to clear. This unit requires still higher ohm and time settings.

Three time steps can thus be provided, one as low as practical and operating for faults up to 80 per cent of the line ohms; a second step, higher than the first by the selective time interval required by the breaker and operating up to a value including about half the next line; and a third step for back-up only.

A time characteristic of this kind may be secured by a group of units functioning on ohms and on time. In an elemental form, the ohm unit is operated by current and restrained by voltage, thereby functioning on impe-

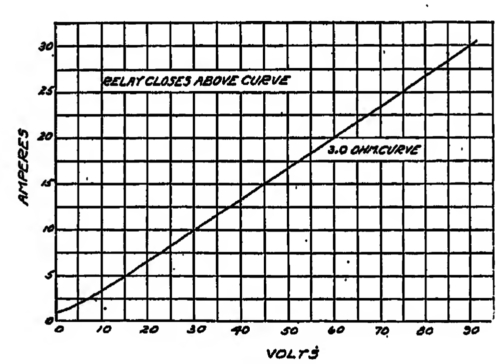

FIG. 7—OPERATING CHARACTERISTIC OF IMPEDANCE RELAY

dance, as shown in Fig. 7. The time desired is measured with precision by an escapement mechanism.

The impedance units shown in Fig. 8 make use of induction elements having shaded poles working through a "disk" cut away at all but the active areas to reduce weight and hasten the action. This construction also provides the needed unstable point which

3. A. I. E. E. TRANS., Vol. XLII, 1923, p. 532—Discussion by P. Ackerman.

permits the "disk" once started to continue to contact for a reasonable increase in impedance. This feature tends to correct for the impedance rise due to a lengthening arc but cannot compensate for a high initial value caused by low current.

The induction type impedance unit shown in Fig. 8 has the time characteristic illustrated in Fig. 9. This time is fast enough to match the associated directional

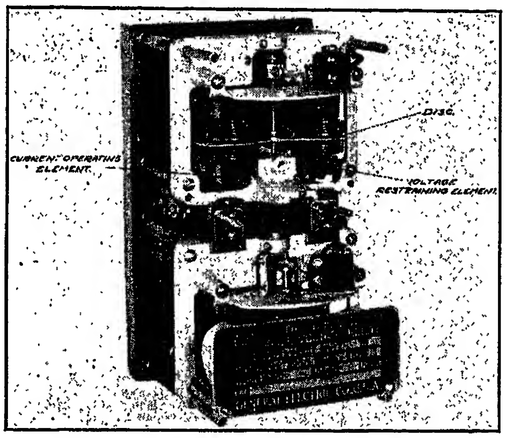

FIG. 8—IMPEDANCE RELAY

unit and, at the same time, deliberate enough to avoid false action on transients, etc.

The operation of the third step, or back-up, is simple in the case illustrated, involving single lines in tandem. When several circuits, which are sources of power, connect to the bus that feeds a faulted line, the subdivision of the total current produces a corresponding increase in the ohms indicated at each of them. For example, if there are two pairs of parallel lines as in Fig.

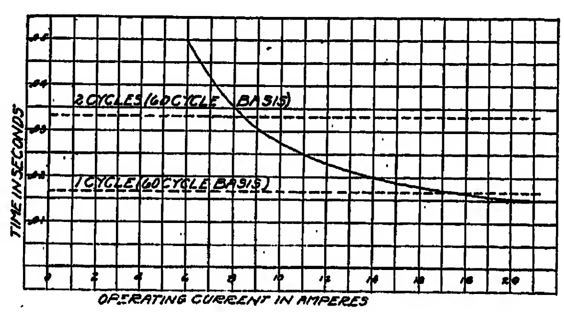

FIG. 9—TIME CURRENT CURVE OF IMPEDANCE RELAY WHEN OPERATING BELOW 90 PER CENT OHMIC SETTING

10, all of the same length and construction, a short at X would indicate W ohms at D^1. If then, in the extreme case, lines A, B, and C all feed equal currents, the ohms indicated at A^1, B^1, and C^1 would be 3 W and at A, B, and C, the ohms indicated would be 4 W and not 2 W.

In setting impedance relays, arc resistance must be taken into account. In fact, on short lines, the arc may have a higher impedance than the line. See composite effect illustrated in Fig. 11. It should be noted that this illustrates a simple mathematical computation based on the assumption that there is no reactance in the arc. It is even more optimistic, therefore, than actual test values indicate. As either metallic or arcing faults are possible, it may be difficult to obtain the proper setting of impedance relays. Even if one were to disregard metallic faults, because of the lesser chance of their occurring, the arc itself is extremely

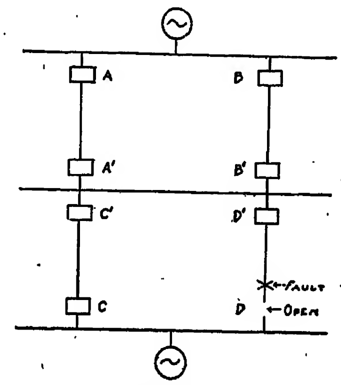

FIG. 10

variable due to changing current and length, as discussed later under field tests. The effect of the arc is, of course, proportionately less as the line increases in length.

REACTANCE RELAYS

The chief component of an arc is resistive although, contrary to a general belief, it also has a very pro-

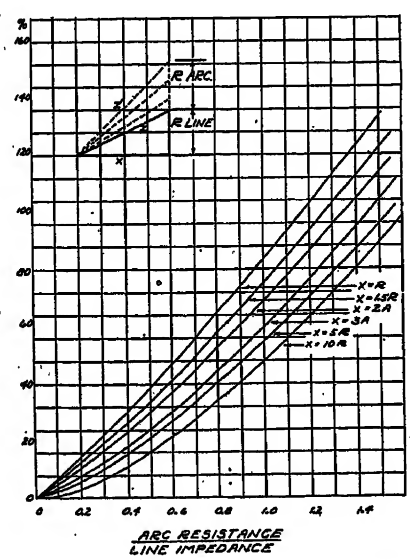

FIG. 11—EFFECT OF ARC RESISTANCE IN INCREASING IMPEDANCE OF FAULTY LINE

nounced reactive effect which may appear in proportions approximating the resistance. This reactive tendency is largely fictitious and becomes decreasingly effective as it is added to line impedance. Furthermore, by the proper choice of instruments, even this fictitious effect can be practically discounted.

Under these conditions, it is submitted that the ohm

unit, most reliable for a distance relay, will work on the inductive reactance component, rather than on impedance.

Directional Action

A distance relay can operate no faster than the directional unit which is a part of it. The shortest time is desired when the voltage and, accordingly, the torque is the lowest. Ample torque under short-circuit conditions must not be secured at the expense of excessive temperature or burden at normal voltage.

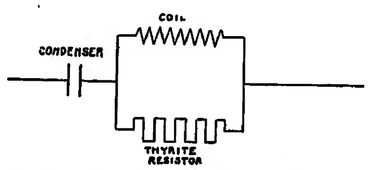

Fig. 12—Connections of the Amplifying Potential Circuit

This problem has been solved by the use of a potential circuit which is resonant at low voltage but not so at full voltage.

This very useful principle can be put to work by tuning the potential coil with a series condenser at low values and detuning at high values by saturation, thereby limiting the current flow by the condenser capacity. This method causes a considerable shift in phase angle and its value is determined by the extent to which this shift may help or hinder.

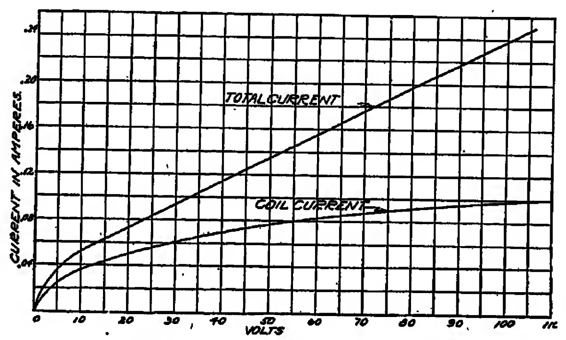

Fig. 13—Current Characteristics of the Amplifying Potential Circuit

In the present instance, a modification of the foregoing is preferred. The circuit is shown in Fig. 12. No saturation of the core is required in this case, and the detuning is accomplished by a thyrite resistor connected in parallel with the coil. Thyrite has the valuable property of changing its resistance to suit the need.[4]

At low voltage the thyrite resistance is so high that practically no current flows through it, leaving the coil and condenser in resonance, and the current through the coil limited only by its own resistance. As the voltage increases the thyrite resistance decreases rapidly (exponentially) until resonance is destroyed. The total current through this circuit and the current through the coil are plotted against secondary volts in Fig. 13.

With thyrite in parallel with the coil and no saturation, the angular relation between the line voltage and the coil voltage is nearly constant as shown in Fig. 14.

A polyphase relay embodying this feature will give speeds of the same order as the distance relay. By providing this relay with a voltage restraining element it can be given a characteristic which will prevent the relay from closing its contacts except when there is a fault on the system. This restraint is secured by the use of a watt element with two potential coils arranged to produce a torque equal to the product of the voltages times the sine of the angle between. If these are excited from two adjacent delta voltages, obtained from the line being protected, the torque will be proportional to the area of the voltage triangle.

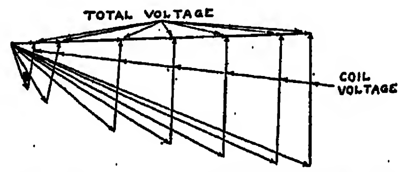

Fig. 14—Phase Relations of the Amplifying Potential Circuit

This feature insures return of the relay to the contact open position immediately after the fault is cleared and prevents false operation due to surges.

The time current curves for a three-phase fault with five volts, at 60 deg. and 10 deg., are shown in Fig. 15, also for a single-phase metallic short. The relay is illustrated in Fig. 16.

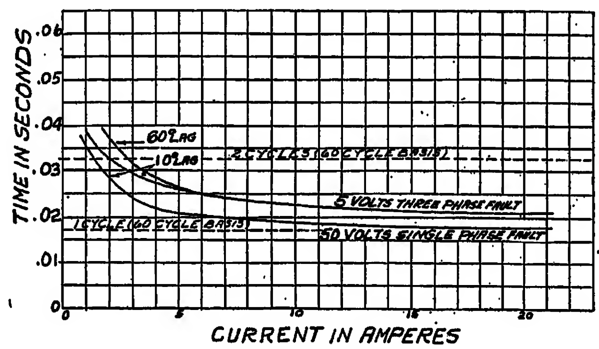

Fig. 15—Polyphase Directional Relay with Voltage Restraint

Simultaneous Tripping at Both Ends *vs.* Cascading

To require that the breaker most distant from the fault must delay tripping until the nearer end has opened, means double time for many disturbances before the circuit can be cleared.

Expressed as a percentage of perfection in simultane-

4. *Thyrite—A New Material for Lightning Arresters,* by K. B. McEachron, A. I. E. E. Quarterly Trans., Vol. 49, April 1930, p. 410.

ous tripping without cascading, the various methods discussed earlier stand about as follows:

Pilot Wire....................100%
Balanced Current.............80%
Distance......................60%

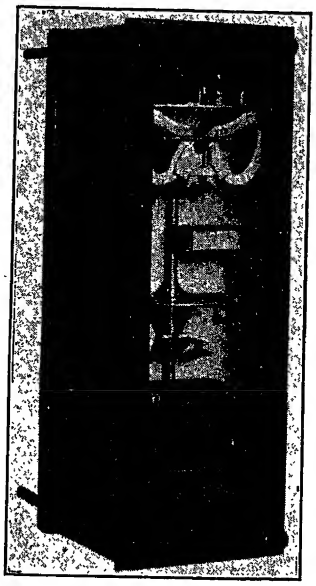

FIG. 16

TESTS

Arc Impedance. In connection with various field tests, the authors have been privileged to secure some data concerning the characteristics of arcs such as occur in case of a flashover of a high-voltage transmission line.

The accuracy of these data is not of a high order since they were obtained in each case as a secondary consideration, without the equipment or preparation which would be needed for a true investigation. The information is included, therefore, in the hope that it will shed its flickering light on a very hazy subject.

It is certain that as the current decreases and approaches an unstable condition, the arc voltage rises rapidly until there is not enough potential in the circuit to support it.

Mr. Paul Ackerman has advanced the theory that an arc will follow the characteristic of an approximately constant value of 400 volts per foot.[5]

Some of the discrepancies in our tests are probably due to the method used to start the arc and to the length of time it has been playing. The presence of the metallic vapor of a fuse wire must have a material effect, particularly at the start. In tests 9 to 12, the arc voltage doubled, on the average, after one-half second, with no appreciable change in current or in arc length.

In another test, the total current in each phase on a three-phase to ground fault was 605 amperes and at the start of the arc the phase to phase voltage was 4500, giving an arc resistance of 7.45 ohms. At the end of 15 cycles of arc, the voltage was 10,280 with practically the same current flow or 16.95 ohms. At the end of 15 cycles, one breaker opened, reducing the current to 322 amperes. The arc lengthened and the voltage continued to rise to a value of 61,000 volts, 40 cycles after the start of the fault.

Low-Voltage Tests. The correct setting of distance relays is dependent upon accurate data on the impedance or reactance of the line in question. Usually this is readily obtainable by calculation though it may be sometimes advisable to check this in the field. Such a test is very easily made with the use of a small current (say 10 amperes) secured from the regular test source and supplied directly to the line through a load box. The usual test ammeter, voltmeter, and wattmeter tell the entire story.

ACKNOWLEDGMENT

The authors wish to express their thanks to the officials of the New England Power Company and the Tennessee Electric Power Company for the opportunity offered to obtain these field test data, and particularly to Messrs. E. E. George, C. F. Powers, and H. H. Spencer, for their assistance.

Discussion

For discussion of this paper see page 1239.

TABLE I.
MISCELLANEOUS ARC DATA

Test No.	System voltage	Position of arc	Approx. length of arc in ft.	Instruments used	Current	Arc voltage	Volts per foot	Arc impedance ohms	Ohms per foot	Arc kv-a.	Kv-a. per foot	Measurement taken after arc duration of
1	110 kv.	ϕ to gr.	4.25	Instrument	960	2,040	480	2.13	0.5	1,960	461	2 seconds
2	110 kv.	ϕ to gr.	4.25	Instrument	640	4,000	940	6.25	1.48	2,560	606	2 seconds
3	110 kv.	ϕ to gr.	4.25	Instrument	640	3,740	870	5.84	1.39	2,295	540	1½ seconds
4	110 kv.	ϕ to gr.	4.25	Instrument	624	3,070	715	4.95	1.16	1,930	453	3 seconds
5	110 kv.	ϕ to gr.	4.25	Instrument	592	3,600	850	6.1	1.44	2,130	500	1½ seconds
6	110 kv.	ϕ to gr.	4.25	Instrument	480	4,560	1070	9.5	2.24	2,190	515	2 seconds
7	115 kv.	ϕ to gr.	6	Oscill.	800	1,500	250	1.8	0.3	1,200	200	0.1 seconds
8	115 kv.	ϕ to gr.	6	Oscill.	605	2,600	433	4.32	0.72	1,570	261	0.05 seconds
9	154 kv.	ϕ to ϕ	12	Oscill.	405	23,100	1916	57	4.75	9,350	779	0.5 seconds
10	154 kv.	ϕ to ϕ	30	Oscill.	385	30,700	1023	78.7	2.6	11,830	394	0.5 seconds
11	154 kv.	ϕ to ϕ	40	Oscill.	385	35,000	875	90.8	2.27	13,500	337	0.5 seconds
12	154 kv.	ϕ to ϕ	40	Oscill.	135	58,500	1462	433.	10.8	7,900	197	0.7 seconds

5. "A Study of Transmission Line Power-Areas," by Paul Ackerman, *The Engineering Journal*, (Canada) May, 1928, p. 309.

High-Speed Protective Relays

BY L. N. CRICHTON[1]
Member, A. I. E. E.

Synopsis.—During the past year or so, studies of stability have been made, to determine methods of preventing loss of synchronism upon the occurrence of faults. Of the several methods found, the most obvious and effective is the high speed isolation of the faulty section of the line; and this, of course, means high speed relays and high speed breakers. Investigation so far has indicated that the time required depends upon the type of fault. Since a three-phase short circuit prevents the flow of synchronizing power, it is the most serious type, and must be cleared in from 6 to 10 cycles. This demands the use of relays which will operate instantaneously.

Recent suggestions have been numerous and these are discussed. This paper covers relays operating at normal frequency and those which have been operated or suggested for operation at higher superimposed frequencies.

While there is a number of difficulties attendant on the design of high-speed relays, (these troubles depending on the type and construction of the relay), high speed relays may still be made to operate on any of the present well known principles such as, impedance principle, current balance principle, etc. They may employ either a mechanical structure or they may make use of thermionic or gas-filled tubes.

Attention is given to a mechanical relay of the impedance type operating with a speed of one cycle or less. Some discussion is also given of the reactance type relay with mention of its limitations, particularly that of the extra time required for its initiating element to operate.

The effect of resistance at the point of fault (arc resistance) is discussed and the conclusion drawn that, for extremely high speed operation, it does not interfere with satisfactory relay performance. This is because of the time required for the arc resistance to increase to an appreciable value.

* * * * *

During the past year or so, studies of system stability have been made with the view of determining the conditions under which large amounts of power can be transmitted without danger of the equipment falling out of step under fault conditions. As a result of these studies, a number of ways of preventing loss of synchronism have been found. The most obvious and effective method of accomplishing this result is the high-speed isolation of the faulty section of the line. While other methods may be employed to increase the stability limit the maximum results cannot be attained on successful interconnections unless high-speed breakers and relays are employed. The necessary speed of clearing faults will depend upon the type of fault. Investigation so far has indicated that a very narrow time zone is available for fault clearing. The most serious conditions occur with the three-phase short circuit because no synchronizing power can flow past the fault. In order to maintain synchronism, faults of this nature must be cleared in 6 to 10 cycles. The double ground fault is not as severe as the three-phase fault and the clearing time may be of the order of 8 to 12 cycles. Next in the order of decreasing severity comes the two-phase fault with clearing times of 15 to 20 cycles. The single-phase-to-ground fault is the least severe and the clearing time may be 20 to 26 cycles. The maximum permissible clearing times for the various types of faults may vary considerably on different systems but the above values indicate the general degree of severity of the different faults and enable one to compare the speed requirements of high-speed relays and breakers with the requirements of the present slow speed equipment.

With high-speed breaker operation, more power can be sent over a transmission line without losing synchronsim on faults; insulator damage due to flashovers will be negligible; the damage to conductors will be practically eliminated and interference with communication circuits reduced.

High-speed circuit breaker operation requires the use of high-speed, selective relays, and these may operate at normal frequency or at a higher frequency.

Normal Frequency Systems

Since high-speed breakers require from 4 to 8 cycles to open the circuit, high-speed relays must operate in 1 cycle or less on a 60-cycle system, in order to keep the total clearing time within the required limits. Many relay operations will be less than 1 cycle, possibly even below ¼ cycle. Some of them will be slower, but, in general, the more severe the trouble the faster should be the relay performance.

High-speed relays may be constructed to operate on any of the present well known principles, such as the impedance principle, the current balance principle, etc., and may employ either a mechanical structure or may make use of thermionic or gas filled tubes.

There is a number of difficulties which present themselves in the design of high-speed relays. The difficulty which will cause the most trouble will depend upon the type and construction of the relay.

One of the most annoying difficulties is that any device which will work at high speed in case of trouble is likely to vibrate badly under load conditions. Another difficulty is that the transient values of short-circuit current may vary through a wide range depending upon the point on the voltage wave at which the trouble occurs.

For any given location of short circuit and condition of connected generator capacity there will be a normal,

1. Meter Engg. Dept., Westinghouse E. & M. Co., Newark, N. J.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

30-140

symmetrical value of short-circuit current. A short circuit may be started at such a point that the peak value of its first alternation may be anywhere from near zero up to, say, 175 per cent of the normal. This effect is more pronounced on systems having a highly inductive circuit. Examples can be seen in oscillograms of almost any high-voltage short-circuit test.

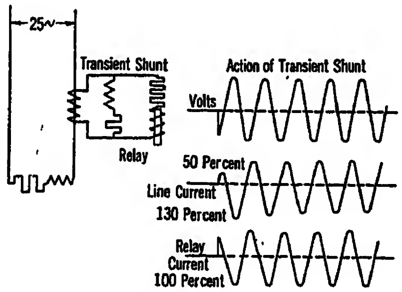

Fig. 1—Transient Shunt and Laboratory Test Results

Showing that the shunt diverts the d-c. component from the over-current relay so that the first half cycle of current is the same value as the sustained current

Simple over-current relay may be compensated by means of a "transient shunt," shown in Fig. 1, so that its performance will be uniform no matter at what point of the voltage wave the short circuit occurs. This shunt is made up of resistance and reactance and is so proportioned that it carries the d-c. component of the unsymmetrical current and allows the normal symmetrical current to flow through the relay.

Where the high-speed relay requires a directional element, a further difficulty is introduced and a more or less definite limitation is placed upon the speed of operation.

It is necessary to make sure that a directional relay integrates the conditions existing in the power circuit over a considerable period of time. Except at unity power factor, the flow of power is always alternating so that the direction of trouble cannot be instantaneously determined. The oscillograms in Fig. 12 show some of the conditions which exist when the current is suddenly reversed in a transmission line. These curves were made in the laboratory and do not represent the

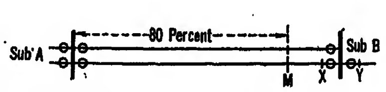

Fig. 2—Illustrating the Difficulty that the Relays at Sub *A* will have in Distinguishing Between Trouble at *X* and *Y* and in Determining Whether the Point *X* is on the Top or Bottom Line

usual condition because the reversed current is smaller than the normal current. It is, however, a common occurrence. Three examples are given showing the reversal at different points in the current wave and the transient current is clearly shown under two of these conditions. Particular attention should be paid to the power wave in order that a better appreciation may be had of the difficulties under which a directional element must operate. At first glance, it appears that one-half cycle of current must be integrated before a determination of the direction can be made but, by manipulation, this may be brought down to one-quarter cycle.

Differential Relays

On parallel lines, differential relays might be used and can easily clear the majority of troubles by opening the breakers simultaneously at each end of the line. However, it is well recognized that when trouble is close to one bus (*X* Fig. 2) the relays at the other bus cannot tell which is the bad line and must wait until the closer relay has operated before they can operate. This is what has been called "sequential" operation.

This type of protection requires the addition of some other relays to be used when one of the parallel lines is not in service. Also, most operators believe that some form of "back-up" protection should be used to care for a possible balanced fault on both lines or for a quite probable fault on the neighboring bus, both of which troubles could not be distinguished by balanced relays. It therefore seems most reasonable to use relays of the distance type and let them care for all kinds of trouble. Distance relays, either of the impedance or reactance

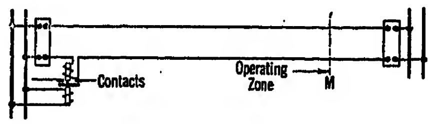

Fig. 3—The Simple, High-Speed, Impedance Relay

type can be connected to their respective circuit breakers without any provision for changing connections or changing adjustments when line conditions are changed.

Impedance Relays

The impedance relay will not eliminate sequential operation because (refer to Fig. 2) the two impedance relays at substation *A* cannot distinguish trouble at *X* any better than differential relays can. Furthermore, a relay at substation *A* cannot distinguish between a short circuit at *X* and one at *Y* if these two points are both close to the bus bars. It is therefore necessary to limit the operation of relays at substation *A* to a zone extending from the relay to *M*. This zone will be approximately 80 per cent of the length of the line section but it will vary depending upon the nature of the fault and the accuracy of the relay. Theoretically, if the zone has a length of 75 per cent for a short circuit between two wires it will have a value of 83.6 per cent for a three-wire short circuit. Double grounds will be practically the same as the two-wire short circuit, if there is no extra resistance at the point of fault.

The fundamental design of this type of relay, Fig. 3, is simple. A current coil attempts to close the contacts but is restrained by the voltage coil. The two coils are so proportioned that they balance each other when

a short circuit occurs at the point M. If the trouble is closer than that point the relay will operate, if it is farther away the relay will not operate. This device is instantaneous in the usual meaning of the term but, of course, it will operate faster when the trouble is close to it. Fig. 4 shows a characteristic time curve of the high-speed element as it is at present developed.

In order to care for the section of the line beyond the instantaneous zone, it has been proposed to use a definite time relay whose operation is initiated by a

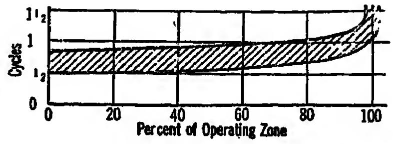

FIG. 4—A CHARACTERISTIC TIME CURVE OF AN IMPEDANCE RELAY ADJUSTED FOR OPERATION ON A LINE OF MODERATE LENGTH.

When used on a short section the time may be slightly greater

second impedance relay set to operate over a longer zone. This should be sufficient protection but, to satisfy a frequent requirement, a second longer time relay operated by a third impedance element has been added for back-up protection to operate in case the breaker at the next station should fail to open as expected. Several sections of transmission line representing part of a network are shown in Fig. 5 with the relay time steps superimposed on top of the line. The setting of one relay operating in the reverse direction is shown below the line in order to emphasize the overlapping of the two operating zones.

It will be observed that if trouble occurs between the points M and N, which represents about 60 per cent of the length of the section, both breakers will open at high speed. When the trouble is outside this zone, only the nearest breaker will open rapidly.

The distance elements and also the time relays are so

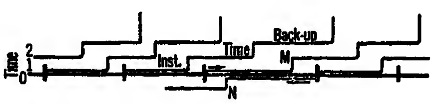

FIG. 5—A SECTION OF TRANSMISSION LINE HAVING SEVERAL SUBSTATIONS

Showing the method of adjusting the instantaneous and time element impedance relay

designed that they will restore themselves instantly if the trouble is cleared by the opening of other breakers.

DIRECTIONAL ELEMENT

Conventional induction type directional elements would be too slow for high-speed relays but a modification has been made which will do fairly well if the voltage can always be kept above 20 per cent of normal. For unbalanced short circuits this is satisfactory if the customary connection is used which permits at least one relay of a set to obtain its voltage from an unaffected phase. For three-phase faults this type of directional element will not be satisfactory, particularly because three-phase faults are most serious and must be cleared with the highest possible speed. One of several methods which has been suggested for overcoming this trouble is to drive continuously a small synchronous motor having a sufficient flywheel effect so that it can keep its proper phase position during the line dis-

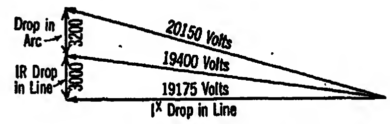

FIG. 6—EFFECT OF RESISTANCE OF AN 8-FT. ARC ON THE IMPEDANCE OF 50 MI. OF SHORT-CIRCUITED 220-KV. LINE

Insulators on all three phases assumed to have flashed over simultaneously

turbance. (Fig. 8.) Of course this motor will not stay in step for any great length of time but we are concerned with only the first few cycles. This scheme has another characteristic which has occasionally been wanted in the past. Some power systems are equipped with grounding switches, and relays are desired which will properly select and cut out the proper line when this switch is accidentally closed. Of course, under

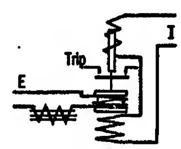

FIG. 7—SIMPLE REACTANCE RELAY

The balance point is where $I^2 = E\,I \sin\phi$ which, simplified, is $I = E \sin\phi$

this condition there is no voltage available for operating the ordinary directional relay. This scheme has not been useful in the past when power directional relays required an appreciable time to operate, but it should work beautifully for high-speed relays which are expected to operate immediately after the start of the trouble. This voltage-sustaining motor need not be considered a part of any individual relay. Rather, it

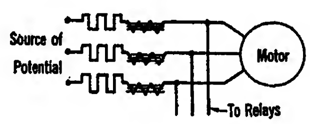

FIG. 8—MOTOR SO CONNECTED THAT IT WILL MAINTAIN VOLTAGE ON THE POWER DIRECTIONAL COILS OF A RELAY EVEN THOUGH THE POTENTIAL ON THE LINE MAY BE REDUCED TO ZERO

should be connected to the relay potential bus and might better be considered an adjunct to the potential transformers.

REACTANCE RELAYS

The effect of resistance at the point of fault in shortening the operating zone is frequently mentioned, but a number of years experience with relays of the impedance type indicates that this is not serious, at least for short circuits. In a short circuit, as distinguished from a

ground, the only resistance can be that of an arc. A remarkable set of tests made by Mr. P. Ackerman several years ago showed that long arcs of heavy current values have a potential across them of about 400 volts per foot. Some unpublished tests made in Germany gave a potential of 360 volts per foot. This does not indicate that impedance relays will be adversely affected by the arc, provided they work fast enough. As an illustration assume that a 220-kv. line has an arc formed between two line conductors. This arc will be about 25 ft. long and, at 400 volts per foot, will have a total drop of 10,000 volts across it which is about 4.5 per cent of normal. This arc voltage has been depended upon for years to operate power directional relays but it is not of sufficient magnitude to affect adversely the operation of distance relays. If the short circuit is close to the relay this arc voltage will be too small to prevent the relay from operating and if the trouble is near the far end of the operating zone its vectorial relation at right angles to the reactance of the line, will be such that it will not seriously change the length of this zone. Fig. 5 is a simple vector diagram for a 50-mile 220-kv. line wherein a short circuit current of 500 amperes has been assumed. Although the voltage across the arc is 15 per cent of the total voltage, this total is only 4 per cent more than what it would have been for a metallic short circuit. This represents the same, decrease 4 per cent, in the operating zone length.

Of course, if the arc is not interrupted promptly, it will increase in length with a consequent increase in the voltage across its terminals. This increase in arc voltage will reduce the current somewhat and this current reduction may, in turn, increase the resistance of the arc, this circle of effects continuing until the arc voltage becomes a large fraction of the normal line voltage. But this requires time. Tests on two different power systems have shown that the arc remains stable and of low resistance for 5 or 6 cycles. It is therefore reasonable to assert that the effect of the arc resistance can be ignored in the operation of high-speed relays except possibly on very short section of line or on systems where the short-circuit current is small. Neither of these limitations will ordinarily apply to the large systems which are under discussion.

The same argument cannot be so easily applied to ground faults because it is conceivable that the earth has considerable resistance at the point where the fault occurs. It is unlikely that a 220-kv. conductor will ever fall to the ground but some object could be brought into contact with it. Under such conditions the ground resistance might amount to several hundred ohms. Even the flashover of an insulator might have a high resistance if there were no overhead ground wires, because the tower ground might be poor. It is possible to construct a reactance relay for ground protection, which will nullify the effect of the fault resistance to a large extent. A relay utilizing the reactance principle can be made in a manner similar to the impedance relay except that the restraining coil, instead of being operated by voltage, should be constructed as a wattless component indicator (Fig. 7). For a single-phase system, this is easy to apply, but difficulty is encountered on a three-phase system because of the different kind of faults which occur. Where an impedance relay is used it is customary to have one set of relays to care for short circuits between wires and another set to care for grounds. The relay having the least restraining voltage is the one which should operate. In a reactance type of relay the phase relations are different for different classes of faults, and therefore the reactive components are different. If then, a relay is so connected that it will operate properly when one wire is grounded it may operate backwards when two wires are grounded because, although the voltages are about the same, the currents are in a different phase position. In order to correct this difficulty, lock-out relays can be used which will cut-out the ground protec-

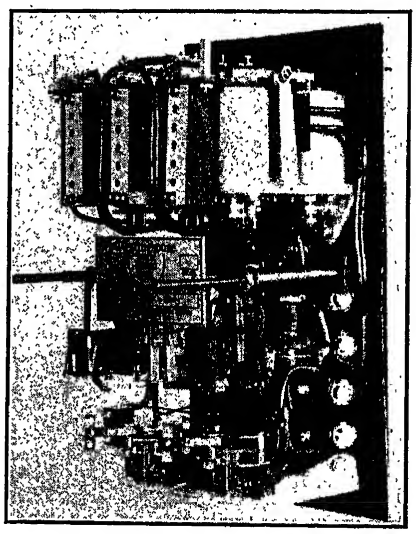

Fig. 9—High-Speed Impedance Relay with Directional Element and with Short-Time and Back-Up Time Elements

tion relays whenever there is excessive current in more than one of the line wires. Because of the additional complication of the reactance relay, it may be preferable to use impedance relays on systems having overhead ground wires and good soil conditions.

The preceding discussion considers the various elements which go to make up a high-speed relay operating at normal frequency. The complete device having all the necessary elements contained in one case are shown in Fig. 9 which illustrates a single-phase high-speed directional impedance relay. It has a high speed, distance time limit, and time limit back-up protection as shown in Fig. 5. To protect completely a three-phase line, three of these relays are used to take care of short circuits between wires and three other relays to care for grounds. If the ground relays are of the reactance type, each is so connected that it uses line

current and the corresponding star voltage. If of the impedance type, they are connected so that they all make use of residual current in their current coils but each one uses a different star voltage. These ground relays may have no directional elements of their own but may make use of the directional elements which are contained in the line relays.

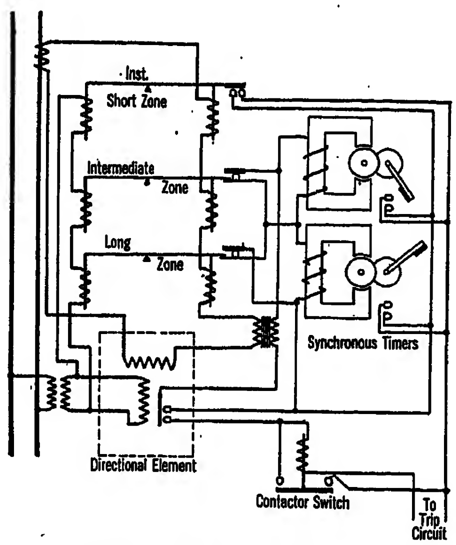

FIG. 10—HIGH-SPEED IMPEDANCE RELAY SHOWING DIRECTIONAL ELEMENT AND THE TWO SMALL TIMING MOTORS OPERATED BY A TRANSFORMER IN THE CURRENT CIRCUIT

EXAMPLE OF IMPEDANCE RELAY INSTALLATION

This relay for transmission lines has not, up to the time this paper is written, been placed in actual operating service. However, the principles involved have been quite thoroughly tried out in single-phase railway service for more than a year.

This type of relay has been applied to 11,000-volt trolley wires which are connected to closely spaced substations fed from a high-voltage transmission line. If trouble occurs close to a bus, the voltage may be

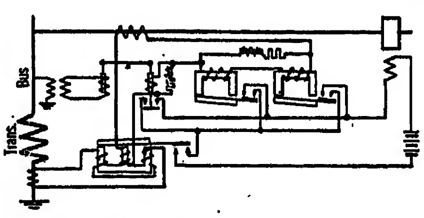

FIG. 11—HIGH-SPEED RELAY INSTALLATION FOR 11-KV. TROLLEY WIRES SHOWING DIRECTIONAL ELEMENT, IMPEDANCE ELEMENT, INSTANTANEOUS OVER-CURRENT ELEMENT, TIME OVER-CURRENT ELEMENT, AND TRANSIENT SHUNTS

lowered so much on the high-voltage transmission line that comparatively little current is supplied by the neighboring substations. Then, as soon as the breaker opens at the near station a current much heavier than any load will usually flow in from the other end. Hence, for this location of fault, proper selectivity will be obtained by the use of high-speed over-current relays at both breakers. But for faults between substations, impedance relays are used so that simultaneous operation is obtained.

This relay arrangement shown in Fig. 11, consists of a high-speed impedance element backed up by a high-speed over-current element. Additional back-up protection to care for the failure of the proper breaker to open and to care for some unusual line conditions consists of an over-current relay set to operate after a short period of time. The directional element is polarized by the neutral current of the power transformers, an excellent arrangement on a system of this kind.

This relay when applied to a 25-cycle system will operate in an average time of less than 0.25 cycle.

THE USE OF THERMIONIC AND GAS-FILLED TUBES

The use of devices of these types has been suggested by many engineers because of some of their obvious advantages. Work along this line is progressing rapidly and there is no reason why impedance relays, including directional elements, should not be constructed of such material. Many engineers are surprised that tubes have not been used before this time and a few general observations regarding them may be of interest.

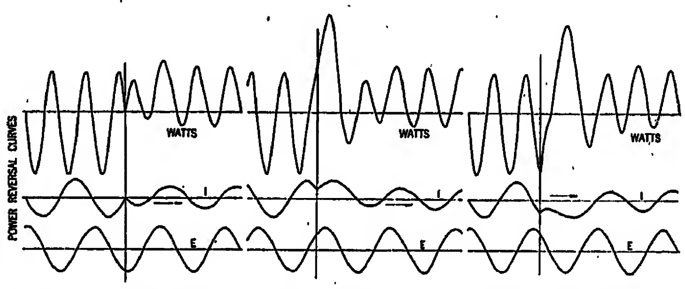

FIG. 12—REVERSAL OF CURRENT AT THREE DIFFERENT POINTS IN THE VOLTAGE WAVE OF A TRANSMISSION LINE

Showing the transient effects in current and power flow

The tube is faster than any mechanical device having the same burden on the current and potential transformers. It will probably be difficult to obtain the extremely high speeds which might be expected, because of the time constants of the various electrical circuits. But then, speeds much below 0.3 cycle appear difficult to attain because of the necessary time required by the directional element.

Some objection has been raised against the use of tubes having hot cathodes but this should not be considered too seriously if other compensating advantages are obtained. It is likely that a life of one or two years may be attained and, in any case, the filament circuits can be supervised so that an alarm will be given if any tube burns out.

Because of the high values of trip currents which high-speed breakers will probably require, any tube type of relay must be especially made to carry a much greater load than is customary in radio receiving equipment. This will probably require the use of tubes containing gas to assist in carrying the current.

This use of gas in the tubes has brought out two unexpected short-comings. Since the action of these tubes involves ionization of the gas, some time is required for the operation to be completed and it has been found that, near the critical point of discrimination, the tubes are neither fast nor accurate. Some tests which were made on a tube type of relay showed that it was no more accurate than a mechanical device. The fault was possibly in the circuits and further work will, no doubt, result in considerable improvement.

High-Frequency Schemes

In order to overcome sequential operation and thus increase the speed of clearing troubles, two solutions

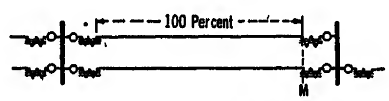

Fig. 13—Illustrating the Use of Reactors to Overcome the Difficulties Shown in Fig. 2

have been proposed. Both of them are expensive. One is the use of a reactor in the transmission line where it connects to the bus. This, in effect, insures that a line fault always occurs some distance away from the bus, so that the trouble will be within the operating zone of impedance relays, or the current in the two lines at the other end of a parallel section will be so unbalanced that differential relays can operate simultaneously. A simple illustration of this arrangement is shown in Fig. 13. In order to secure proper selectivity

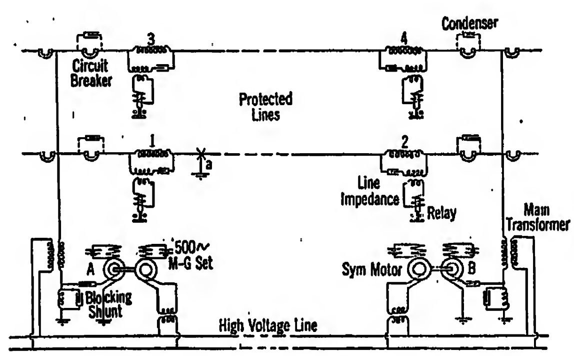

Fig. 14—Superimposed High Frequency (500 Cycle) as it Might be Applied to the Trolley Wires of an 11-Kv. Single-Phase Railroad System

this reactor should be equivalent to about 10 per cent of the reactance of the line, so it is obvious that such a device will cost a considerable amount, particularly when used on high-voltage lines.

The only other apparent methods of securing simultaneous operation is by means of some high-frequency scheme.

Some of the high-frequency schemes which have been suggested will increase the speed of relay operation, others will simply make sure that the breakers at both ends of the line will be opened simultaneously at the speed which may be attained by normal frequency relays. A superimposed scheme has been suggested, carrier current is in use, and several proposed schemes are being investigated. Consideration has been given to the use of both moderate frequencies of the order of 500 cycles and carrier current frequencies of from, say, 20 to 100 kilocycles.

Superimposed High Frequency

The superimposed high-frequency scheme described by Mr. L. R. Ludwig before the Institute June 25, 1928, promises to become of considerable importance. The method is to superimpose a high frequency on the power system at various points, probably at every place where there is a power transformer, and depend upon the short-circuiting of this high-frequency circuit to sectionalize the transmission line. The reason for using the high frequency is that it can be more cheaply blocked out of line sections than can the normal frequency. Instead of the simple but expensive reactors

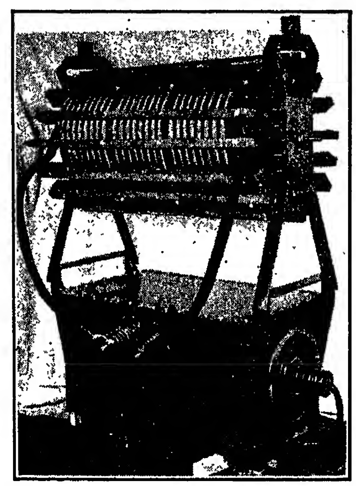

Fig. 15—An Anti-Resonant Shunt for Blocking the Current in the 500 Cycle System Shown in Fig. 14.

shown in Fig. 13, the high frequency can be impeded by anti-resonant shunts composed of small reactors and capacitors as shown in Fig. 14. An anti-resonant shunt intended for an 11,000-volt railway system and capable of withstanding 50,000 amperes short-circuit current at 25 cycles is shown in Fig. 15 and is obviously not too expensive. It is intended to be hung from the bus structure by suspension insulators and will not require any particularly heavy structure to support it.

It is of interest to note that, although the anti-resonant shunt can be designed to have a high impedance to the flow of the high-frequency current, this acts as a resistance and is at right angles to the reactance of the line so that it is not as effective as might at first be expected.

For a three-phase system, a three-phase generator may be used so that short circuits between wires as well as short circuits to ground can be isolated. Directional relays can easily be provided on such a system although they will not usually be required.

Carrier Current Schemes

All of the carrier current schemes that have been suggested, make use of some characteristic of the fundamental current for their operation or else they depend upon normal frequency relays which send out a high-frequency impulse to the other end of the section. They are all equivalent to the use of pilot wires. Various frequencies have been suggested ranging from 500 cycles to 100 kilocycles but the difference in frequency does not materially affect the principles involved; neither does it appear that any particular range of frequency is less likely to be interfered with by the power arc disturbance which occurs during the trouble. The advantage of a higher frequency seems to be that it is somewhat easier to block it out of circuits where it is not desired.

The method which has been installed on at least two power systems in this country and which has been described by Mr. A. S. Fitzgerald, of the General Electric Company, makes use of the effect that, when trouble occurs in a section, the current in the two ends of the wire is flowing to the fault in opposite directions. A sending set and a receiving set at each end of the line are both polarized by these currents so that an impulse will be sent out from one end when the current is in a certain direction and it can only be received by the receiver at the other end when the current is in the opposite direction. A simplified diagram is shown in Fig. 16 which is taken from Mr. Fitzgerald's paper.

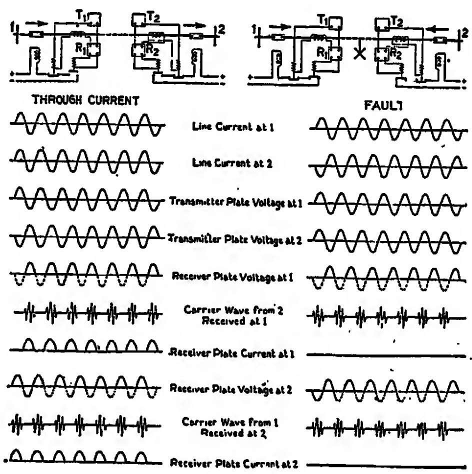

Fig. 16—Fitzgerald's Carrier-Current Scheme

Normal frequency over-current relays operate to trip the breaker. If the instantaneous currents at each end of the line have the same direction, indicating that the line itself is sound, a carrier signal is received preventing the over-current relays from tripping the breakers

Another scheme is based upon the fact that at least one end of the line section can always be opened simultaneously by normal frequency relays no matter where trouble occurs. The idea is to have this relay not only open its own breaker but to send an impulse to the other end of the line and open the other breaker. An advantage of this arrangement is that the high frequency is not actually used in the majority of cases of trouble and if it should fail the effect would not be so serious as would be the case if it were always depended upon. Even if it should fail on a case of trouble near one end of the line, the result would be sequential operation, not a total failure to clear trouble. Of course, all carrier current schemes can readily be interlocked with normal frequency relays so that false operation when there is no trouble, can be prevented.

A 500-cycle carrier current scheme of this type

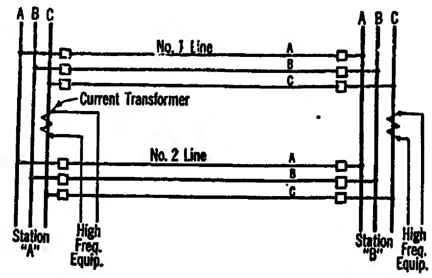

Fig. 17—A 500-Cycle Carrier Current Scheme Applicable to Parallel Lines or Loops

When an instantaneous relay at either end of a line operates it opens its own breaker and sends an impulse to the other end of the line to open the other breaker

which is applicable to parallel lines is shown in Fig. 17. Two frequencies, say 480 cycles and 600 cycles, will be introduced when desired, one frequency to trip the breakers on No. 1 line and the other frequency to trip the breakers on No. 2 line. Two generators will be run continuously at each end and the proper impulses sent out whenever any normal frequency relay operates. This impulse will be received at the other end by the relay which is tuned to it, and the proper breaker will be tripped. Obviously this scheme cannot work when

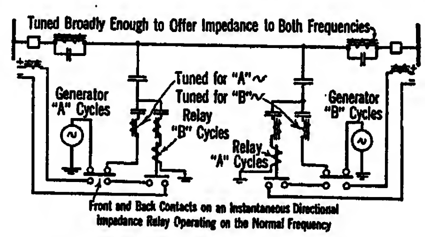

Fig. 18—Suggested High-Frequency Carrier-Current Scheme

The carrier is sent continuously. The operation of any normal frequency relay will interrupt the carrier and thus transmit an operating impulse to the breaker at the other end of the line

one of the lines is cut out of service. However, it can be applied to loops of any reasonable number of sections in which case there must be as many frequencies used as there are sections of line.

Another scheme which can be applied to any form of network is to use a carrier current to send the tripping impulses from one end of the section to the other and to put anti-resonant shunts in the line so as to keep each carrier impulse within its own section. This is one of the most likely schemes which has been suggested

because of its flexibility. One method of accomplishing this is shown in Fig. 18 with the interlocking connections between the high-frequency and the normal frequency relays.

Power Arc Disturbances

There is no doubt but that the arc which occurs at the point of faults must be given serious consideration when considering the questions of high-frequency relay. Often there is no way to send a carrier impulse to the next station except over the line which is in trouble. It is conceivable that this arc may send a false signal. The difficulty is that any shock to a tuned circuit will cause it to oscillate and this shock may be applied to the tuned circuits of receiving sets over a large part of the power system. This may result in a tripping impulse being improperly given. It will not help much to have the carrier running continuously and interrupt it as a signal because the arc disturbance may be of such a nature that the stoppage of the carrier will not be detected.

The answer to this difficulty is, apparently, to raise the power level. By this is meant to increase the amount of power used by the carrier equipment to such a point that it will not be seriously influenced by the disturbance set-up at the point of fault.

Summary

Present day developments in the central station industry demand high-speed protective relays in order that the systems may be kept stable.

Suitable designs are now available and a single-phase installation has received a thorough test in exacting service for the past eighteen months.

Improvements are now being made so that the relay art will keep pace with the circuit breaker development.

Normal frequency relays of the distance type are recommended.

The shortcoming of these relays is in the frequent troubles which can only be cleared sequentially by them.

High-frequency protection must be used to overcome sequential operation on long lines where pilot wires are out of the question.

The use of high frequency is largely an economic problem. If the lines have sufficient capacity, if the breakers are fast enough, and if the excitation response is quick enough, simultaneous breaker operation will not be necessary. But where all these factors or a sufficient weight of them cannot be economically attained, then high-frequency methods should be used.

Acknowledgment

In addition to the acknowledgments made in the text, the writer is indebted to the following members of the Westinghouse organization whose work has been studied in the preparation of this paper: Messrs. R. C. Bergvall, R. C. Curtis, S. L. Goldsborough, R. D. Evans, and H. A. McLaughlin, who is now with the Central Hudson Gas & Electric Company.

Discussion

MODERN REQUIREMENTS FOR PROTECTIVE RELAYS ON IMPORTANT SYSTEM INTERCONNECTIONS

(Traver and Kennedy)

HIGH SPEED PROTECTIVE RELAYS

(Crichton)

H. H. Spencer: There appears to be a real limit below which it is unwise to carry the operating times of reactance or impedance relays such as described in the papers by Messrs. Crichton, Traver and Kennedy. In general these relays consist of element operated by current and restrained by voltage. A fixed ratio between these two determines the operating point and the ratio is commonly referred to as impedance. It should be pointed out, however, that the operating point of the relay is only an apparent impedance and is equal to

$$``Z" = \frac{R\,i + L\,\dfrac{d\,i}{d\,t}}{i}$$

Only in steady state does this become a true impedance $R + j\,X$. Since the predominating transient in alternating-current short circuits is a decrement $\dfrac{d\,i}{d\,t}$ is less than $j\,\omega\,I$ and the apparent impedance is less than the vector sum of resistance and steady-state reactance. The unfortunate thing is that the difference between the apparent impedance and the true impedance is a function of the decrement and therefore of the connected capacity which is the thing we are trying to avoid in all these relay schemes. Possibly a transient shunt such as Mr. Crichton has described but with taps to take care of the various values of connected capacity might eliminate this difficulty, but it appears to the writer that it would be better to make the minimum time of impedance or reactance relays long enough to allow the worst of the decrement to expire. Dependence upon other relays, as for example, balanced current, can be placed for extremely high-speed operation.

A. S. Fitzgerald: Since in two of the papers as well as in the discussion, there have been references to the carrier current relay scheme you may be interested to have some further information about this system.

It is now several years since this development was first embarked upon. It represented an entirely new departure in relay methods. As such, it was necessarily an undertaking likely to take a considerable time to bring to completion. Indeed, due to the general advancement of ideas with regard to relaying practise, during the last few years, we have had to considerably revise our plans as to what the carrier current system should accomplish. So that in addition to spending time on the development of carrier current methods we have also had to undertake a good deal of development work relating to features of this relay scheme, which are not concerned primarily with carrier current, as such, in order to keep abreast of changes in relay requirements during this time.

For example, when this work was commenced time delay methods of selective protection were still in good standing. Thus the first carrier current relay field tests were made on the basis of a time delay scheme which enabled the tube filaments, on the occurrence of an excess current, to be brought up to operating temperature. The connections also, as described in the original paper,* involved a system of starting, receiver, and tripping relays, operating in sequence. The total time of operation was about one-half second.

This scheme enabled us to develop, and to try out in the field, the carrier current circuits and methods of operation. After this had been done and promising results obtained, it became clear

*Journal A. I. E. E., October 1927.

that the general trend or relaying practise was rapidly moving towards higher speeds of operation. It was therefore found better to keep the tube filaments continuously at operating temperature and to avoid relay connections involving sequence operation. Therefore, an entirely new scheme of relay connections was devised, capable of operating reliably in one-tenth of a second.

As well as higher speeds of operation there has also been a tendency toward lower current settings. In developing the original carrier current relay scheme we were anxious to avoid a multiplicity of auxiliary apparatus, for purposes of power supply. It was found that with direct operation from bushing transformers successful operation could be obtained at currents of two or three hundred amperes. At that date it was felt that this might be of practical use. However, in actual applications of this scheme much lower tripping currents have been required and a great deal of the time spent in developing this scheme has been devoted to this aspect of the problem.

Everyone who has experience of relay development realizes the very limited value of any tests or data other than actual operating records. This is mainly why relay developments take such a long time. However, due to the splendid co-operation of the operating companies, of which I cannot speak too highly, we have now records of at least one hundred short circuits on lines on which the carrier current system has been installed. Many of these have been actual faults. Others have been applied intentionally during field tests and a large number of oscillograph records have been obtained.

With this data available I think you will agree with me that we are beginning to know enough about this scheme to attempt to draw a few conclusions. I believe you will find these rather surprising.

For purposes of discussion, we may conveniently divide this scheme into two separate parts, namely, the power frequency part and the carrier current section. The former includes the relays and the current transformer excitation circuit by means of which the carrier current apparatus is energized and set to work to transmit to the other end of the line a signal indicating the power conditions. The carrier current part includes the vacuum tubes, the carrier current apparatus and circuits, and the transmission and reception of carrier current over the high line under fault conditions.

There is nothing about the power frequency part of this scheme that relay engineers will have any difficulty with, but the carrier current and vacuum tube part of the business is something with which we, as relay engineers, are unfamiliar, and with regard to which very little engineering experience is available. Any feelings of doubt or apprehension which we may entertain as to the success of this scheme very naturally refer to the carrier current feature.

This feeling, which is entirely logical, is to be noted in Mr. Crichton's paper where he raises the question as to the effects which the power arc may have on the carrier current operation. I doubt if there is any one feature of this work with respect to which the engineers following this development felt more concerned. There was absolutely no data to go upon whatever. I remember that plans were made to install a carrier current receiver, and an operation recorder on a high line, and, with no carrier current transmitter at all, see if we could get any data showing operation due to power arcs and similar disturbances. This work, however, was delayed due to other field tests on this scheme. When we came to check up on the records which we were obtaining we did not find a single instance where evidence of interference by the power arc could be traced. Nor have we been able to, up to the present date. Due to this we were unable to justify the expense of the special test referred to.

Indeed the surprising result of the operating record of this scheme is that the carrier current part of it has come through with flying colors. It has never given us any trouble at all. Of course, we have had our difficulties. These must be expected in such an undertaking. But it is a fact that all the troubles we have encountered have been associated with the 60-cycle circuits and not with the high-frequency apparatus. We have changed our relay design and connections to get higher speeds. And we have had a number of failures to operate because the fault current was too low to furnish enough excitation. But we have not found it necessary to make any substantial modification in the design of the carrier apparatus.

As you may know this system is installed on one of the Big Creek lines on the Southern California Edison system*. The power company feels that the carrier current scheme has proven successful and recently I learned that during March heavy sleet conditions caused eight faults on this line in two days and that correct operation was obtained, every time.

P. Ackerman: I am very gratified to see the profession in general gradually come around and accept the need of the basic principle of instantaneous protection for which I have been fighting for the last fifteen years.

In particular I am pleased to see both large manufacturing companies accept finally, for fast line protection, the same basic principle of multi distance range protection as I have developed and successfully applied for the past ten years. As has been pointed out in my paper, this principle of protection for long transmission lines, along with the differential principle for station apparatus must be considered the key to the universal solution toward 100 per cent system protection which could only be still further improved in effectiveness by a carrier current pilot protection or a similar arrangement, which would clear all line short circuits simultaneously at both ends.

I note from the two papers that great strides are being made to obtain as low as half a cycle or even shorter relay clearance, based on 60-cycle current. The impedance relay has inherently this characteristic, but the directional relay doubtlessly offers decided obstacles for different reasons. It is very doubtful as to whether such short timing, with its complications, is warranted, at least at this instant. One- to two-cycle relay time would appear sufficient at present, as this would present only a small fraction of the proposed circuit breaker timing of six to eight cycles, which latter appears to be the present limitation.

I believe that the successful and universal solution of the stability problem will have to be sought in an effective system layout rather than in the solution of excessively fast breakers, as has been pointed out in my paper.

H. W. Haberl: With all new relays pointing toward instantaneous operation and possibly simultaneous clearance, I wish to point out a few important points and a method by which they can be overcome, even by using the older style of distance relay and its distance proportional time curve.

The new style distance relay time curves, as shown in the papers presented by Messrs. Traver and Kennedy, and also by Mr. Crichton, are represented by the step principle in which the instantaneous feature reaches only to about 80 per cent of the line length. This is not objectionable on single lines but, where two or more lines are on the same tower (assuming the fault to be 20 per cent line distance from either station) the trouble is cleared at one end after a predetermined time during which period the arc is very liable to communicate to the good line.

The scheme I wish to present is an instantaneous clearance to 100 per cent line length, provided both lines are in service. One line being out of service the time for the remaining line is either the distance proportional or the newer step principle, depending on the style of relays used. With one line out of service the disadvantage of having the line clear at one end by definite time is not objectionable here because the power arc cannot communicate trouble to another circuit.

**Electrical World*, March 22, 1930.

Fig. 1 shows a combination distance relay and balanced relay scheme. Under normal conditions or under through faults the duo-directional relay is in the mid-position and therefore the circuit opening auxiliary relays are short-circuiting the resistors. All relays have full voltage, therefore standard back up protection is in force, but with the trouble occurring on one line the duo-directional relay contacts towards the faulty line, operating the auxiliary relay on the faulty line which inserts the 3000-ohm resistor in the voltage coils of the faulty line relays which, in turn, operate instantaneously. The auxiliary switch of the oil breaker makes the instantaneous feature inoperative on the remaining line.

C. Litchtenberg: Protective relays are now recognized as an essential part of every electricity generation, transmission and distribution system. Their characteristics are requiring marked changes from time to time as interconnections are increased and improved service continuity is demanded.

Initially a protective relay was just an auxiliary trip for a circuit interrupter. It was first just an overload trip. Two or more of these were set far enough apart so that some degree of selection was obtained when faults occurred. As the number of circuits increased, however, the limit of this type of selectivity was soon reached. About this time there was introduced the time delay feature to obtain greater selectivity. It inaugurated what may be called the second phase of development. It

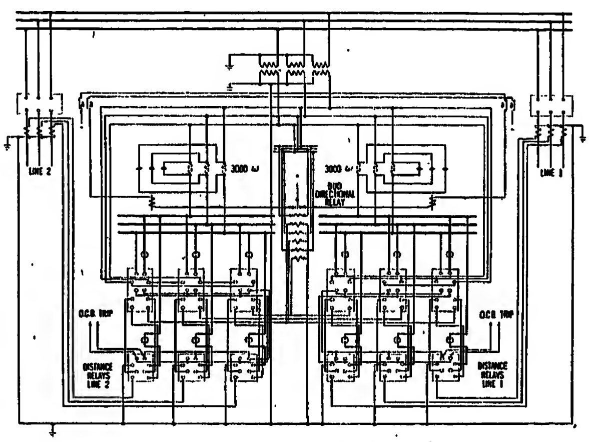

Fig. 1—Connections for Combination Distance Relay and Balanced Relay Scheme

brought first the definite time delay dash pots and air bellows. Then came the inverse time delay with air bellows. These, however, had inherent limitations. They did not permit accurate setting or accurate repetitive operation. They were replaced for more exacting service by the induction disk time delay relays.

The common method of obtaining selectivity with all of the time delay features was by suitable settings of the pick up or starting current and the time delay. One of these is electrical in its performance. It depends upon circuit conditions. The other is mechanical or magnetic in its operation. It is relatively independent of circuit conditions. In addition the minimum time obtainable with reasonable accuracy for any of these is in the order of 0.1 second, or 6 cycles on a 60-cycle circuit. Consequently, where a number of circuits is to be protected and the time settings are additive, the last relay in the chain had to be set at from 0.5 second to 1.0 second, that is, from 30 cycles to 60 cycles, on a 60-cycle circuit.

For simple radial feeder systems with few series relay steps such settings permit excellent performance. However, when the number of series steps of relaying exceeds three or four, the maximum time delay becomes an important item. If it is too long it may result in low-voltage conditions during system disturbances and may even cause further system disturbances, resulting in unnecessary interruptions.

Many years of experience have shown that the induction disk time delay relay is almost as good as can be expected when all conditions are considered. Therefore, it became imperative to find new ways of meeting service requirements for protective relays which would more promptly and accurately clear faulty sections from the system.

Studies led to the third phase of the development. This is the present stage which employs circuit currents and circuit characteristics for not only starting the operation of the protective relay, but also for selecting the most effective circuit interrupter to trip.

Several of the newer developments in relays to meet these changed conditions have been described in the papers presented by Messrs. Traver and Kennedy, and Crichton. These indicate that while a minimum of 0.1 second was to be expected with the induction disk form of relay, the newer distance and balanced circuit relays can be expected to complete their performance in somewhat less than 0.01 second. This is in about ½ cycle on a 60-cycle circuit. The improved performance is accomplished by utilizing resistance, reactance and capacity, in combination with circuit current changes. It brings the protective relay development well up to the development of circuit interrupting devices, which now permit clearing disturbances on circuits up to and including those operating on 220 kilovolts within 8 cycles of the appearance of the disturbance at the protected point.

The fourth phase of protective relay development is about to begin. It will probably tend to a closer realization of the "anticipatory relay" which engineers have hoped to secure from time to time. It will no doubt utilize vacuum tubes and vacuum tube circuits for following circuit current wave shape and magnitude changes. As a result, it may be expected that the minimum time of operation of relays may be reduced from 0.5 cycle as at present, to the order of 0.05 cycle or even less on a 60-cycle basis. The further advances will no doubt be made available as soon as the circuit interrupting requirements are such as to warrent removing faults more promptly to improve service continuity.

O. C. Traver—L. F. Kennedy: We agree with Mr. Ackerman concerning the difficulty in determining the length of an arc, and in order to overcome this the majority of those referred to in Table I of our paper were drawn in still air, between electrodes spaced a definite distance. Photographs of these arcs indicated no material tendency to rise and lengthen before interrupted.

Answering Mr. Ackerman's question as to the speed of the carrier current pilot protective equipment, the present installation operates in 0.1 second and there is prospect of cutting this to approximately one-half. In general, this action is simultaneous at the two ends, without cascading, for faults over the entire length.

Reference has been made by several of the speakers to the limit in speed for directional distance equipment. Operation in two or three cycles seems quite in keeping with the circuit breaker time and offers a very distinct and reasonable reduction. This two or three cycles is based not on operation under favorable conditions, but upon severe faults close by which leave practically no potential and, accordingly, aggravate the likelihood of instability.

We do not consider this speed to be an ultimate but rather a logical step for the present. We have secured much lower time but consider it unwise to tempt inaccurate results through premature action. Further reductions will be forthcoming to match the inevitable increase in circuit breaker speed.

L. N. Crichton: Mr. Spencer's remarks concerning the effect of the transient current on the performance of high speed impedance relays, are pertinent and deserve consideration. If the system is highly reactive the effect of the transient is notice-

able for several alternations. An example of this is on railway trolley circuits where the spacing between wire and return conductors (rails) is large and the reactance consequently high. But the usual high voltage system has a sufficiently high short-circuit power factor so that the transient is not appreciable after, say, two alternations. This can result in an error only when the trouble is near the balance point of the impedance relay. Because the forces are nearly balanced, the resultant effect on the moving parts is slight. Hence the inertia of these parts makes the relay act in a sluggish manner as shown in Fig. 14 of the paper. The requirement of Mr. Spencer's analysis is, therefore, satisfied without any particular effort on the part of the relay designer. Tests which have recently been made on a large power system prove that the transient shunt is not necessary with the 60-cycle relay shown in Fig. 9.

Where the shunt is really needed is on 25-cycle railway systems where only ¼ cycle is allowed for the relay operation. Here the shunt is necessary for accuracy. The transient is not always larger than the steady state current. Sometimes the first alternation is smaller. The shunt equalizes all these conditions.

Referring to Mr. Fitzgerald's description of the carrier current systems, the industry is indebted to him for the splendid work he has done and to the power companies for their cooperation. But the question still remains, is it worth what it costs? Probably it will be justified on some important and heavily loaded lines.

One- to two-cycle relay time, as suggested by Mr. Ackerman should be satisfactory for present day applications. But we wanted our relay to be suitable for any demand which may occur during the next few years.

The scheme suggested by Mr. Haberl is clever and is illustrative of the resourcefulness which operating men must employ in order to harmonize the operating conditions with the lines and equipment which they have available.

Many engineers have dreamed of the anticipatory relay mentioned by Mr. Lichtenberg and when it is discovered it may perform a function which is different from our present relays. Perhaps it will anticipate trouble and remove it from the circuit before the circuit has broken down. For some troubles this seems absurd but not so absurd for the most frequent trouble of all, lightning. However, this is some time in the future. In the meantime, progress is continuing along conventional paths with the principal objects of maintaining stability and preventing power lines from being burned down by the arc which follows a flashover.

Directional Ground Relays

BY E. E. GEORGE[1] and R. H. BENNETT, Jr.[2]

Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—This paper deals with the paramount importance of ground protection on transmission systems which has been demonstrated by experience over the past few years. It presents the advantages of ground relays and shows that the disadvantages sometimes attributed to them are not well founded or have been overcome.

A number of standard and special applications of relays for directional ground protection are described and illustrated by sketches showing connections. The application of these schemes is discussed and their desirability and feasibility supported by records of operating experience.

Attention is called to the point that high-speed relaying will soon be an accomplished fact. High-speed relaying will be needed in both phase and ground protection to take full advantage of high breaker speed.

In the testing of relays adequate test facilities are necessary to save time and to insure correct test results. Attention is called to the desirability of making staged tests at system voltage to insure correct relay operation and for their experimental value in developing improved forms of protection.

* * * * *

LESS than four years ago, there appeared the following summary of protective relay practise for transmission systems.

"Electrical faults on a transmission or distribution system consist mainly of short circuits and grounds. The protective scheme is primarily designed to operate on values of current caused by short circuits between phases. . . . If the neutral of the system is grounded, the method of grounding has an important bearing on the protective scheme. Where the neutral system is dead grounded, or grounded by means of a low resistance, the protective scheme designed to operate on short circuit usually also protects against grounds."

The above quotation will be recognized by many as taken from the Relay Handbook which was prepared by a joint committee of the N. E. L. A. and A. I. E. E., and undoubtedly represented the latest and best thought as of 1926.

Late in December, 1929, the *Electrical World,* in reporting the World Engineering Congress at Tokyo, made the following statements:

"During the past five and one-half years of 220-kv. operation on one system there have been 148 cases of trouble and in all cases a flow of ground current was recorded. Even though the trouble resulted from widely varying causes, such as birds, fires, floods, lightning, sleet, contact with telephone wires and contact with trees, etc., ground current is always indicated. Accordingly, on one system the decision has been made to rely for protection solely upon residual or ground current relays. . . . Phase relays are retained on most systems, but many engineers are agreed that phase to ground protection is the most essential for 220-kv. operation."

With such a remarkable evolution in transmission relay practise so recently accomplished, it may be desirable to point out some of the developments that have come about more or less unheralded. For instance, the argument as to whether high-tension neutrals should be grounded or ungrounded is a thing of the past, and the industry has come to accept grounded neutral operation as economically advantageous and technically indispensable. The only related argument left is as to the extent of grounding,—whether it is to be solid, resistance, reactance, or resonant grounding. If we make liberal allowance for the wide variety of conditions to be met, it may be unreasonable to assume that any one of these varieties will ever be generally accepted as standard.

Fundamentally, neutral grounding operates to facilitate protection by providing at the switching station a circuit for fault current independent of the load current. Overload protection utilizes common circuits for fault and load currents and can distinguish fault current from load current only when the former is large compared with the latter. This requirement was generally met a few years ago. Voltages were lower, systems smaller, and interconnections practically unknown. Charging currents and arcing grounds were of academic interest only.

Relay protection has kept pace fully with the increase in voltage, in length of lines, and in growth of regional networks. The past few years have been times of history making, rather than history writing; and although ground protection has been the chief development utilized in meeting the requirements of modern transmission systems, nowhere in technical literature today does there seem to be any adequate presentation of the importance of ground relaying. Nevertheless, it is a matter of common verbal admission among relay engineers of transmission companies that ground protection is more important than phase protection, and that with most types of transmission construction above 66 kv., phase protection is of very questionable value, excepting, of course, a few promising recent developments. Only recently has there been available a sufficient knowledge of fault phenomena to justify on

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a theoretical basis the general opinion that ground relaying becomes of more importance as transmission voltages go higher, and that at voltages of 66 kv. and above, ground protection is of more importance than phase protection. The efficiency of ground relay protection which has resulted in its popularity of late years is largely due to the following factors.

Advantages of Ground Relays

1. Ground relays are independent for all practical purposes, of surges due to switching, synchronizing, motor starting, condenser starting, etc.

2. Ground protection is based on the fact that the current flowing in the relay under normal conditions is zero and, therefore, such protection is even more sensitive than differential or balanced protection with phase relays.

3. Ground relays can easily be made to operate at higher speeds. Directional ground relays now operate on some systems as fast as 5 cycles and one type of special induction relay used for initiating the operation of oscillographic equipment operates in 2 cycles.

4. The high attenuation of ground fault current with distance results in automatic selectivity. The zero sequence impedance of lines is usually considered to be 3½ to 4 times the positive sequence impedance, which means that distance provides several times as much discrimination on ground faults as it does on phase faults. The application of inverse time characteristic relays to ground protection is thus fairly easy.

5. Ground relays are applicable to systems either solidly grounded or grounded through impedance, although they are applied more easily and more satisfactorily to solidly grounded systems.

6. Ground relays are applicable to multi-grounded systems. With the increasing number of interconnections, such systems will soon result, even though we started out originally with each system grounded at one central point.

7. Ground relays are applicable to networks and to intercompany tie lines because they are independent of the location of generation, and thereby afford dispatchers maximum freedom in allocating power supply. This point has often been overlooked. Relay schemes should avoid unnecessary restrictions on the location and amount of generation, and ground relaying does this much more thoroughly than any available form of phase protection.

8. Ground currents can now be calculated with sufficient precision to enable ground relays to be set correctly.

9. Equipment is now available to check ground current and the tripping time of ground relays under actual fault operation on the power system.

10. Ground relays operate fast enough to clear up faults with a minimum amount of damage to insulators, bushings, and windings. Most high-tension line failures can be cleared quickly enough by ground relays to prevent burning the line down, except in cases of direct lightning strokes.

11. Ground relays usually clear up lightning flash-overs, wires swinging into trees or structures, etc., before the arc has time to spread into adjacent phases. Single-phase-to-ground faults seldom result in instability, and fast clearing of such troubles therefore prevents out of step conditions and loss of synchronous load. In the case of horizontal construction, lightning very frequently causes two phases to flash over to ground simultaneously, but ground relays will clear a double ground fault about as fast as a single ground fault, under most conditions. Ground relays give no protection against three phases shorted or grounded, but such faults are rare except with closely spaced horizontal construction and high insulation to ground.

12. Ground relays prevent lines down on the ground from remaining energized and endangering lives and property. A single damage suit may cost more than providing grounded star-connected transformers and ground relays for several substations.

13. Phase protection has to be proportioned to the maximum carrying capacity of the largest section of a circuit in order not to limit the economic capacity of the circuit. Small branches connected to heavy circuits cannot be protected by such maximum settings of phase relays, but ground relays may be set low enough to protect small transformers or small conductors.

14. Very frequently it is difficult or impossible to install differential protection on transformers or rotating equipment, but in practically all such cases ground relays can be used to give satisfactory protection, especially if the transformer or generator windings are not grounded. This is usually the case on step-down transformer stations and on large motors and synchronous condensers. Of course, the system neutral must be grounded at some other point.

15. In general, systems of different voltage will not interchange ground current except when coupled by auto-transformers or by three-winding transformers with two-grounded Y windings. It is, therefore, possible to set ground relays on one voltage system independently of those on another voltage system. This is not true of phase protection, and in most high-tension systems it is necessary to coordinate the phase relay settings even when switches are separated by transformation.

Advantages of Directional Ground Relays

1. Directional ground relays do not necessarily require potential connections.

2. Directional ground relays may be made independent of fault power factor for all practical purposes.

3. The direction of normal power flow and reactive flow have no effect on directional ground relays.

4. It is unnecessary to interlock phase and ground relays when directional ground relays are used.

5. Directional ground relays have more highly

inverse characteristics than any other type of relay. Their characteristic curves are almost rectangular hyperbolas, which are, of course, the theoretically perfect form of inverse characteristic.

Disadvantages of Ground Relays

Any discussion of the merits of plain ground relays and directional ground relays would not be complete without reference to the objections raised against such relays by those who are not using them.

1. "Ground relays often operate too fast and trip out a line on remote trouble."

This is entirely a matter of setting. Many systems operate with less than one per cent of incorrect operations due to such causes. Ground relays with low-current taps and fast time settings cannot be used indiscriminately on networks any more than could phase relays with similar current and time settings. However, on radial feeders it is often possible to use ground relay settings of five to 15 per cent of the phase settings and considerably shorter time. The increased zone of protection is readily apparent. Nothing but ground protection has ever been devised that will protect 11-kv. rural distribution lines 50 miles long and of small conductor size, as we frequently have today.

2. "Ground currents are difficult to calculate."

This has been substantially true until within the last year or two. Much progress has been made recently. Several companies use direct current calculating tables to determine ground currents. Long-hand calculation can be used without especial difficulty by making use of several assumptions justified by field test during the last year and described in the serial report of the Southeastern Division, Electrical Apparatus Committee entitled, "Calculation of Ground Currents."

3. "Ground currents are difficult to measure."

This is no more true of ground fault current than of phase fault current. Any comment on either should take note of recent developments and improvements in high-speed graphic ammeters and the oscillographic equipment.

4. "Ground relays are unnecessary if a system is grounded at every supply transformer, as every ground fault will take enough current to operate phase relays."

This may be true on short lines and at the lower voltages but it is well known that even phase fault currents at higher voltages may be less than maximum load currents, in which case, phase protection of any ordinary overload or reverse power type is unreliable and hazardous.

It is very interesting to note that the new distance relays now available for phase protection measure reactance or other circuit characteristics, rather than phase current. The successful use of distance relays lends more weight to our conclusion that any successful protection for high-voltage transmission systems must be independent of load current.

Non-Directional Ground Protection

As an introduction to directional relay protection, a non-directional ground or residual relay connected in the neutral of three line current transformers is shown in Fig. 1. This connection is well known and very generally used. Where bushing current transformers are used it is desirable in all ground relay applications to use relays with fairly low volt ampere burden so that the current transformer ratio will not be effected.

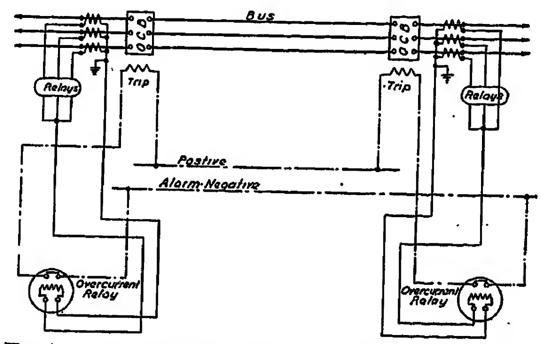

Fig. 1—Non Directional Ground Protection

In order to follow better any of the complicated or unusual directional ground relay schemes, reference may be made first to a non-directional standard hookup for directional ground relays shown in Fig. 2. This scheme may be applied to one or more lines whether they are tie lines or feeders. It is applicable to loops or networks only if the faulty line carries substantially all of the outgoing ground current from the station in question. This scheme is, therefore, not generally applicable to short parallel lines or to a short loop of

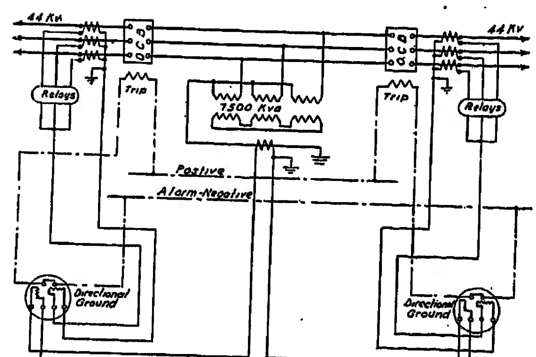

Fig. 2—Standard Directional Ground Protection (A)

only two links, as both lines will tend to relay simultaneously on far end trouble, and inverse time characteristics must be utilized to clear the far end first.

Directional ground relays wired as shown in Fig. 1 are used instead of plain ground relays in the following cases:

1. On tie lines which may carry incoming ground current from other grounded points.

2. On short lines or intercompany tie lines where highly inverse selectivity with distance is necessary.

3. On radial feeders where the far end step-down transformer is grounded on the high side for any reason. An outfeed directional ground relay may be set fast to protect the line and transformer, but its directional characteristic will prevent tripping out the line when feeding back through the bus to a fault on some other line.

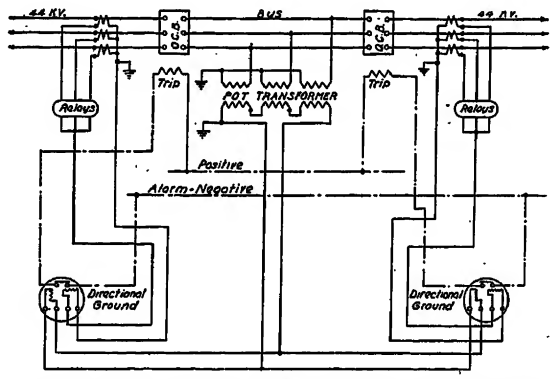

FIG. 3—STANDARD DIRECTIONAL GROUND PROTECTION (B)

4. To get a more satisfactory current setting than is possible with the line current transformers (usually bushing type). As one element of the directional ground relays is connected to a bus type current transformer in the neutral ground lead of the power transformer, any ratio from 1:1 to 1000:1 may be used for the bus type current transformer. The effective ratio between primary and secondary currents will be the square root of the sum of the squares of the line and neutral current transformer ratios.

STANDARD DIRECTIONAL GROUND PROTECTION

Another scheme of plain directional ground protection is shown in Fig. 3 in which the relay is polarized by potential rather than current. For this purpose it uses an inside delta potential obtained from the secondary of three potential transformers *Y* connected and grounded. In general the application of this scheme parallels that of Fig. 2, the only fundamental difference between the two schemes being the means of polarizing the ground relay, one using residual current and the other residual voltage.

DIRECTIONAL GROUND PROTECTION OF LOOPS

Fig. 4 shows the scheme of directional ground protection used on a 110-kv. loop. The fundamental feature of this scheme is the cross connection. This is shown here as completed through an auxiliary current transformer, but this is required only on unsymmetrical loops. On symmetrical loops and on parallel lines the auto-current transformer may be omitted, since equal primary currents in the same direction in each line will neutralize each other in the secondary circuit. When the auto-current transformer is required, it should be connected so that both secondary currents will neutralize each other on trouble on the far end bus, and thus prevent tripping either line. The ground current supplied by the home and grounding transformer is used chiefly for directional discrimination and not for time selectivity; therefore, a small grounding bank can be used if necessary, particularly at the receiving end of the loop.

The standard wiring scheme for Fig. 4 is as follows: The secondary of the neutral current transformers goes through the upper elements of two directional ground relays in series. The lower elements of both relays are in series and are connected to the bushing current transformer secondary neutrals in multiple. These bushing current transformers and relays have symmetrical polarity but are reversed at the common or multiple connection so that the lower elements of the relays receive the difference of the residual line currents when ground current is going out of both lines. When ground current is feeding through, the residual currents in both lines add in the relay circuit. The characteristics of this connection are as follows:

With both lines in service and either line in trouble, and the loop open at the far end, the bad line trips correctly and very quickly. With both lines in service and the loop closed at the far end, the line carrying the heaviest fault current trips correctly but very slowly, giving opportunity for the other end to clear and relieve the fault current on the good line. If both lines are in service and in trouble and the fault current is balanced, neither switch will operate. If the home bus is in trouble and the line fault currents are balanced, neither switch will trip. If the home bus is in trouble and the line fault currents are unbalanced, the line carrying the smallest current will trip slowly. The other line will not trip. With only one line in service and in trouble, this line will relay satisfactorily unless the trip circuits

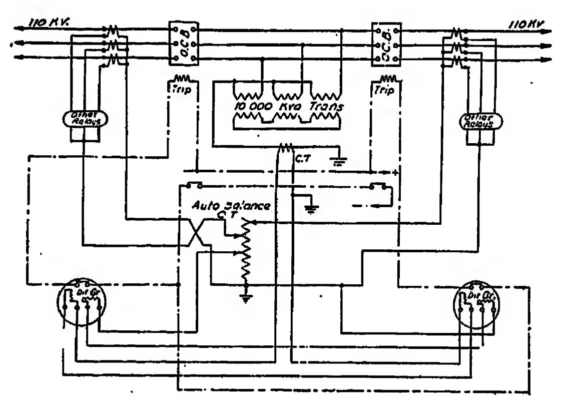

FIG. 4—DIRECTIONAL GROUND PROTECTION ON LOOPS

are interlocked. If the bus goes in trouble with only one line in service, this line will not trip at that end.

This connection will not operate correctly if there are other lines off of the bus at the home end unless some means is provided for making both lines directional. This can be done by standard directional ground relays used as locking relays on the trip circuits.

This scheme may require series "A" switches or

standard locking relays if used on a loop of three or more links so as to prevent the second line tripping too quickly after the first. However, series "A" switches are not desirable at the power supply end of a loop as they do not give single line protection except on back up relays. For such installations, locking relays are better as they will restore directional ground protection on the second line in a few seconds. If one end of the balanced lines is without power supply, protection on the second line for single line operation is usually immaterial.

Directional Ground Protection on Auto-Transformer Ties

Fig. 5 shows an application of directional ground relays to auto-transformer stations or other stations, where the grounding transformer neutral is not brought out but is grounded inside the transformer case. In general this scheme is applicable only to stations with only two transmission lines. It is particularly suitable for auto-transformers with high reactance windings and wide difference between high and intermediate voltages, especially if the intermediate voltage ties closely into a heavily grounded system.

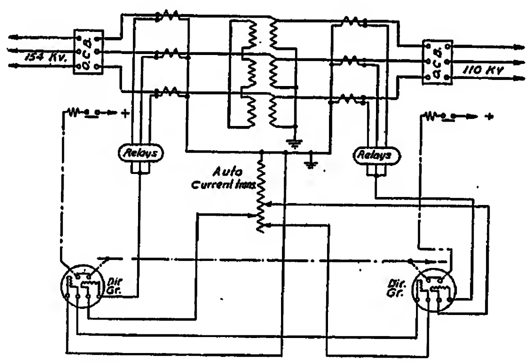

Fig. 5—Directional Ground Protection on Auto-Transformer Ties

In case of a fault on the high-voltage side, such an installation may result in zero or reversed ground current in the auto-transformer neutral, due to the large amount of ground current put out by the intermediate voltage system. The neutral current is, therefore, not suitable for directional discrimination and some other references current must be obtained. Delta current is difficult to get, especially if the auto-transformer is used to supply a load from the delta winding.

The scheme of connections shown in Fig. 5 provides excellent bus protection. No neutral current transformer is required. The scheme is applicable to auto-transformers regardless of ratio. It is very similar in operation to the balanced ground relay scheme for auto-transformers. The line bushing current transformers are connected with symmetrical polarity and are connected symmetrically to the lower elements of their respective directional ground relays. The bushing current transformer neutral circuits are then connected totalizing so that the upper coil would receive the sum of the line currents if both lines were feeding out. On through feed, the upper coil receives the difference of the line currents, which is the ground current put out by the station. In case of auto-transformers, it is necessary to install an auto-current transformer in one current transformer secondary before the multiple connection is made. If there is no reversal of neutral current, this auto-current transformer can be set in the ratio of voltage transformation of the power transformer so as to cancel out the through ground current.

This scheme operates correctly with either line in trouble. It also gives perfect bus protection with one or both lines in service, whether they are balanced or not. This is a disadvantage on loop circuits and this scheme should not be used in place of balanced relays on a loop or parallel lines. It is satisfactory where the outgoing circuits are not connected together at any other point for any appreciable interchange of ground current. This scheme, naturally, will not operate if there is no supply or fault current at the station, but it functions satisfactorily with one line out of service and will trip on either bus or line trouble. The relays work rapidly when current is going in the same direction in the two lines and as fast as ordinary directional ground relays connected in the ordinary manner using a current transformer in the transformer neutral. This plan provides the same current in the upper element of the relay on single line faults and in the same direction as a neutral current transformer does. However, in case of both lines being in trouble, the sum of the two line currents flows in the lower elements providing very fast operation. If the bus goes in trouble, the current is in the opposite direction to that provided by a neutral current transformer, resulting in very fast bus protection.

This scheme is particularly useful where the power transformer neutral is not brought out, or where a proper ratio neutral current transformer cannot be obtained, or where the direction of current in the neutral is indeterminate. In the last case it has the same advantage of using circulating current in the delta for polarizing directional relays, but is independent of the delta load current and has the same other advantages mentioned above. Since the line current transformers are usually of considerably lower ratio than neutral current transformers, it provides much more current for the directional ground relays and may require special relays to get high enough settings. It is particularly advantageous on an auto power bank because auto-current transformers can be used to step up the current on one side enough to prevent a net reversal.

If there are additional lines off of the bus besides those from auto transformers, some sort of locking scheme must be used, as a fault on a third line is similar to a fault on the bus.

Balanced Ground Protection on Auto-Transformer Ties

By using a balanced ground relay of the *C D* or *I J* type in place of the two directional ground relays described above, there results a very simple and effective protection for auto-transformers having only one line from each of the two auto windings. This is shown in Fig. 6. An auxiliary auto-current transformer may be used in the current-transformer secondaries on either

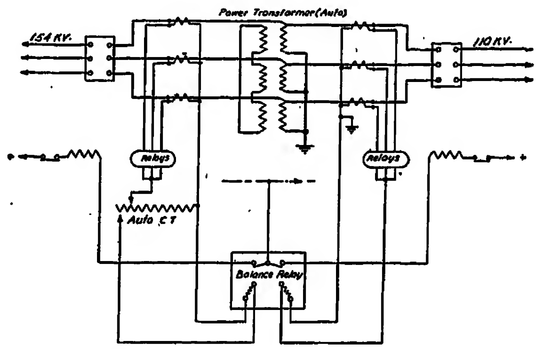

Fig. 6—Balanced Ground Protection

side of the balanced ground relay, so as to compensate for the ratio of transformation of the auto-transformer and also for any difference in current transformer ratios. This results in the flow of ground current through the auto-transformer balancing out in the relay circuit, leaving only the fault current put out by the auto-transformers to operate the balanced ground relay. The current will appear in the side of the relay toward the fault, thus making the balanced relay directional for

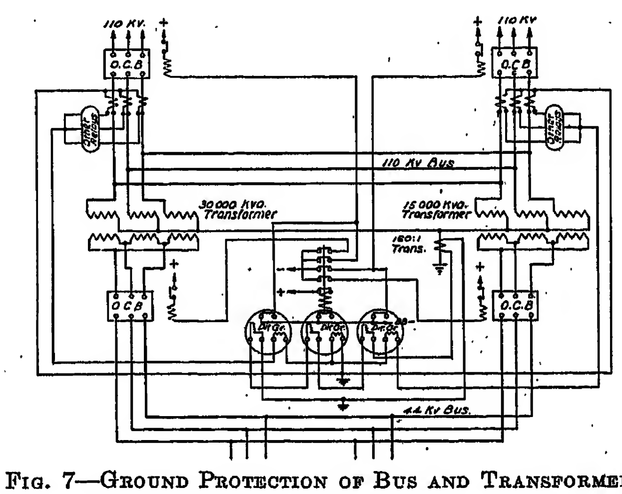

Fig. 7—Ground Protection of Bus and Transformers

ground protection. Although this scheme provides very little in the way of bus protection, it is very simple and effective for directional ground protection of outgoing lines tied through an auto-transformer.

Ground Protection of Bus and Transformers

Fig. 7 shows a scheme for securing fast ground protection on a high-tension bus and high-tension transformer windings without differential protection. Such a scheme is in use at one of our substations where there are two high-tension lines. Three-directional ground relays have the upper coils connected in series to a 15,000-volt current transformer in the neutral of the 110-kv. grounding bank. Two of these directional ground relays are wired as in Fig. 2 and are used as directional ground relays on the two outgoing lines. After going through these relays the neutral of the bushing current transformers are commoned in such a way that the ground currents will add on an infeed to the bus from each line. This common connection is taken through a third directional ground relay which operates through an auxiliary relay to open the line switches and the low side switches on the transformer bank.

This scheme provides fast protection against failures to ground on the bus or high-tension windings of the transformer. It assumes that a source of ground current is available at the other end of each outgoing line. Combined with low side ground relays as shown on Fig. 8 it provides a very satisfactory substitute for

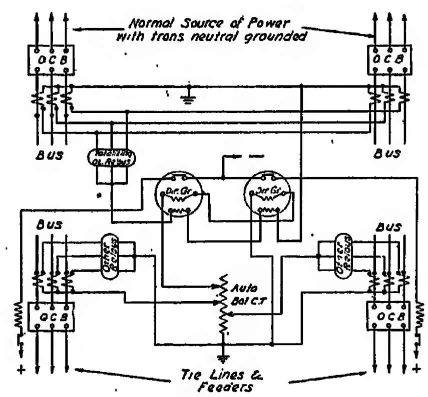

Fig. 8—Directional Ground Protection Without Grounding Transformers

differential protection since practically all bus and transformer troubles either start with failure to ground or develop into such almost immediately.

Directional Ground Relay Protection without Grounding Transformer

In Fig. 8 the ground current fed into the station from the two parallel lines is used to polarize ground relays on two other outgoing lines. Current transformer neutrals from the two incoming lines are connected in parallel and taken through the upper coils of the directional ground relays. In the simple case the neutral of each outgoing line is taken through a directional relay on that line. In Fig. 8 the two outgoing lines form a non-symmetrical loop between four stations, and a scheme of cross connection together with a balancing auto-transformer as shown in Fig. 4 is used. The polarizing of directional ground relays by this scheme requires that a supply of ground current be available at the far end of the two incoming lines and that at least one of these lines be in service at all times. As a substitute for a grounding

bank the scheme has the objections that current transformer ratios are fixed by requirements of metering, other relays, etc., and also that with one incoming line out of service the amount of polarizing current may be small and relay operating time correspondingly increased.

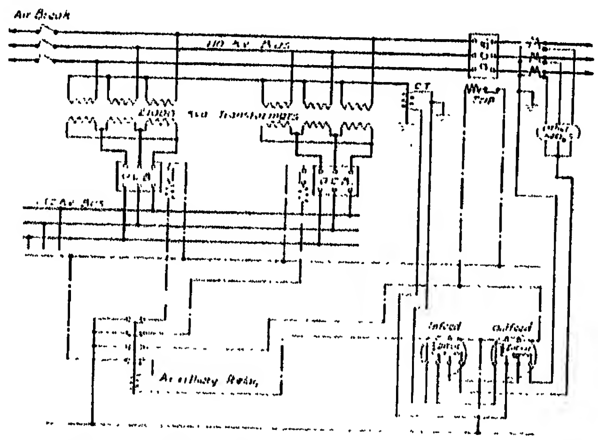

FIG. 9—DIRECTIONAL GROUND PROTECTION ON TWO LINES WITH ONE OIL CIRCUIT BREAKER

DIRECTIONAL GROUND PROTECTION ON TWO LINES WITH ONLY ONE LINE BREAKER

Such protection as shown in Fig. 9 is possible through connections similar to those in Fig. 7. Two directional ground relays are used with the upper coils connected in series to a current transformer in the neutral of the power bank. The neutral circuit from the bushing current transformers on the line breaker is taken through the lower coil of these two relays in series in opposite directions. This scheme considers the section

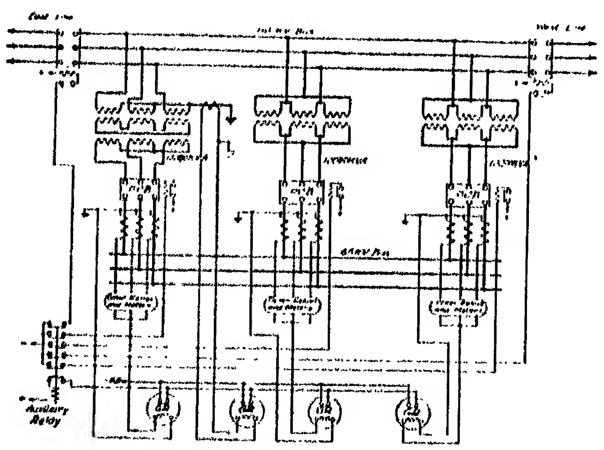

FIG. 10—GROUND PROTECTION OF TRANSFORMERS AND HIGH SIDE BUS

of line tied to the bus through the air break switch as part of the bus. As in Fig. 7 this scheme requires a source of ground current at the other end of the line which is equipped with a breaker. The scheme is not as fast on bus or transformer trouble as Fig. 7 since there is no totalizing of ground current. Of course it does not afford transformer protection against power fed in on the line which has no breaker.

Potential operated directional ground relays can also be utilized, instead of current operated directional ground relays as suggested.

TRANSFORMER AND BUS PROTECTION

Fig. 10 shows how plain ground relays may be used to secure the equivalent of differential protection. A ground relay is connected in the neutral current transformer secondary in the high side neutral ground lead. Ground relays are also connected in the neutral of the current transformers on the low side. Trip circuits of all of these relays operate an auxiliary relay to trip all sources of power to the high-tension bus and transformers.

This scheme requires that the low side bus be supplied by generators with grounded neutral or some other source of ground current. Relays can be set very fast for grounds on the low-tension windings. The protec-

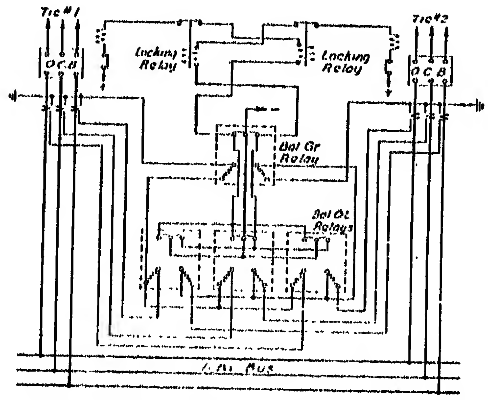

FIG. 11—LOCKING RELAYS FOR BALANCED LINE PROTECTION

tion afforded on the high tension windings is necessarily slow since the ground relay must be selective with line relays. In this installation at Great Falls only one transformer has its neutral grounded. This scheme therefore requires that this transformer be kept in service at all times. The high-tension ground relay also affords back-up protection for the line relays in case the breaker is by-passed or the relays fail to function.

LOCKING RELAYS FOR BALANCED LINE PROTECTION

Where balanced relays without interlocking are used on parallel tie-lines or double-circuit lines many cases have occurred where both lines would relay when only one line was in trouble due either to mechanical back lash in relays or to difference in speed of relay or breaker operation on the two ends of one line. To overcome these troubles it is necessary to interlock the trip circuits so that when one line opens the other line cannot open at the same station for a second or two. Fig. 11 shows

how this can be accomplished by use of locking relays. These relays prevent false operation and at the same time restore protection on the second line in a few seconds. The trip circuits may be interlocked through *A* switches on the breakers, in which case protection is not restored until both lines are in service. In this case some kind of back up protection is needed for single line operation.

Interlocking on loops can be obtained with directional ground relays as described in Fig. 2 with additional advantages. They prevent operation on surges and on backfeed into trouble on a third line when the infeed current will not necessarily be balanced.

Ground Protection without 11-Kv. Breaker or Current Transformers

In Fig. 12 a current transformer and ground relay in the neutral of a small 11-kv. grounding bank furnishes ground protection for a rural feeder fed from the delta power bank. As long as there is only one 11-kv. line a circuit breaker on the 11,000-volt side of the power bank is not required. This scheme illustrates a relatively inexpensive method of ground protection on rural

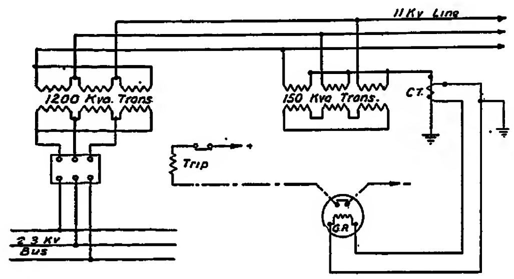

Fig. 12—Ground Protection to 11-Kv. System Without 11-Kv. Oil Circuit Breaker or Current Transformers

feeders. Schemes of this and a similar nature have been used in a number of instances where the load was small and more expensive installations could not be justified. As the mileage of connected 11-kv. line increases the scheme becomes less satisfactory due to the small capacity of the ground bank and its inability to maintain the entire system with balanced voltage to ground.

High Speed Relaying

With the advent of circuit breakers which are intended to clear faults in from 3 to 10 cycles compared with 20 to 60 cycles heretofore, it is very evident that some marked changes in relay protection will have to be worked out immediately. In so far as the necessary changes to get high-speed relaying can be applied to existing relay installations, there will be a marked saving to the industry and a much more prompt adoption of high-speed switching. A high-speed breaker is of little use unless it is operated by high-speed relays, so as to decrease the total time of duration of the fault. In systems where cascaded time settings are used extensively, high-speed breakers and relays cannot be used in certain locations without seriously imparing the protection at other points. Immediate study should therefore be given to the effect of high speed relaying at certain locations and to the possibility of speeding up relay operation at all possible points. It will be found that ground relays are much more susceptible to improvement in this regard than are phase relays. In some locations, the minimum settings of phase relays are determined by starting currents on large motors and cannot be materially lowered.

For nearly a year the authors have been experimenting with faster ground relay settings, and have found the following limitations in present equipment:

1. Back lash is the most serious design defect in directional ground relays. In some cases directional ground relays will close whenever several times pick-up current is sent through their windings in the opening direction and suddenly cut off. This is due to spring and back lash in the various portions of the mechanism which return energy to the disk when released. A special design of mechanism has already been brought out by one manufacturer to eliminate this trouble.

2. The closing adjustment of the three poles of oil circuit breakers is a very important point in connection with high-speed relaying. On a multi-grounded neutral system, the closing of any loaded circuit on only one or two of the three phases will circulate ground current. It is manifestly impossible to adjust circuit breakers so that all three poles will close at the same instant. Frequently breakers get out of adjustment between poles as much as several cycles and this results in heavy ground currents during the closing operation. This factor will always prevent the application of instantaneous relays to high-speed switching.

3. Synchronizing surges. Even with automatic equipment it is impossible to prevent heavy surges of a few cycles duration when paralleling machines and systems. Ground relays are not affected appreciably by synchronizing except in connection with breaker adjustment as noted above.

4. Most present relays have enough inertia in their moving parts that it is difficult to close them in less than 5 to 10 cycles regardless of the time lever setting. At low time settings there is no proportionality between time setting and actual time of operation and it is difficult to get an inverse time lever characteristic with current.

5. Rebound or chattering of the contacts may occur if very high torque is used to get fast operation.

It would be fairly easy to design and use high-speed relays and high-speed breakers if a whole system could be changed over to this equipment at once, but in many cases it is going to be extremely difficult to use high-speed switching and relaying on one part of a system and the present day types on the rest of the system. It would therefore be advantageous to speed up the relays as much as possible on all present installations so

that the gradual changeover to high-speed switching will not mean so much revision in the protective system as a whole.

Records of Fault Current

No matter how well relays are designed and how carefully they are installed and tested and no matter how well the settings are chosen, it is impossible to predetermine all the fault conditions that the relays may have to take care of. It is therefore, absolutely essential to watch the operation of relays in service and to know when they operate and how fast they operate, particularly in complicated transmission networks.

Various types of equipment are now available for recording fault current and other electrical data. Records from such equipment have been found to tell considerable about relay settings, breaker performance, fault phenomena, and the operation of the system including the activities of the station personnel.

The most unexpected and valuable information from such equipment has been the approximate location of permanent line trouble on high-voltage transmission lines. In many cases troubles have been located within two or three miles and it is almost always possible to tell which end of the line patrol should start from in order to locate the fault most promptly.

The records from this equipment have also given fairly complete evidence that there are no surges or flashovers or other faults to ground which clear up without relaying at least enough points to materially reduce the voltage across the fault. Those records have also shown that the relays do not work except when there are faults to be cleared. Both of these points have been under discussion during previous years in connection with ground relay protection.

The two general types of equipment for recording fault current are curve drawing ammeters and oscillographs. The outstanding advantages of the high-speed graphic ammeter are its lower cost, and the instant availability of the record. The advantages of the oscillographic equipment are the much more accurate record, response to variations in fault current, and the fact that the oscillographic equipment gets into operation much more rapidly, therefore recording the first portion of the disturbance. Another advantage of multi-element oscillographic equipment is that simultaneous records of current and voltage can be obtained in their proper phase relation, permitting a determination of power factor, etc.

Either type of equipment is well worth while, and the first is probably more suitable for installation at all important stations on the average system. On account of the increased cost and slightly higher grade maintenance required, oscillographic equipment is better suited to the more important high-voltage stations or to stations where unusual trouble has been experienced and accurate records are necessary.

Staged Tests

As power systems interconnections become more frequent and more complicated, it is likely that some of the simpler and better known relay schemes will prove inadequate. The chief objection to many of the more complicated relay schemes is that they are difficult to test out and to put into operation with the proper connection and settings. It is a difficult problem to phase relays by using low-voltage test current or by using normal load current so that they will operate properly with system voltage fault currents of great magnitude under abnormal conditions. While secondary testing is reasonably adequate for plain overload and ground relays, it is slow and difficult for reverse power and impedance relays, or any other relays having potential connections.

To get away from such difficulties in connecting up and testing out important relay schemes, especially if complicated, several power systems have been checking such installations by actually placing faults on the power system, and having the relay test men watch the operation of the relays, read portable meters, and get oscillographic records. This procedure tells the whole story as to the operation of the protective equipment at all stations involved under actual operating conditions.

The making of such staged tests is one of the most powerful and effective ways of securing the proper operation of relays and other protective equipment. The time and cost involved is usually small and in many cases has been found to be less than the cost of checking out installations by low-voltage tests. Low-voltage tests usually involve a lot of vector diagrams and long arguments as to phase rotation, power factor of the load or interconnection, polarity, correctness of manufacturer's data, etc. Even after low-voltage tests are made in the best manner possible by high grade men, there often result unexplainable errors in connections, and these are usually not detected until the protective equipment fails to operate properly in service. Oftentimes such an installation is then changed radically without much analysis or investigation, and further incorrect operations may result. However, with staged tests, it is generally possible to put the equipment into service with the positive knowledge that it is operating properly, as any errors are almost certain to be discovered on the first staged test and can be corrected and checked on subsequent tests.

Arguments in favor of staged tests have been presented before the A. I. E. E. on several occasions. One of the first articles outlining the advantages of staged system tests was that of Messrs. Sporn and St. Clair, A. I. E. E. Trans., Vol. 46, Feb. 1927, pp. 310, 311, and 314. Those companies which have used such tests for relay work seem to be thoroughly convinced of their value and are now making such tests more frequently than ever before.

Many staged tests for checking relay operation have

been made by the Duquesne Light Company and these have been described in various publications.[3-6]

In some cases it has been found advantageous to check relay connections for the first time by staged tests without making any attempt to determine the proper connections by vector diagrams or by low-voltage tests. In any case the staged test is the final authority, and if a staged test can be made immediately after the new installation, without undue trouble or expense, there is very little reason for men on the drafting board or in the construction department spending the time usually required to figure out the proper connections beforehand.

It should not be assumed that staged tests can be used under all conditions for all relay installations, but it is suggested that considerable benefit may be had by considering every installation as to the possibility of checking by staged tests and making such tests wherever practicable. Where such tests cannot be made, it is of course, necessary to fall back on the usual methods of calculations and low-voltage test.

Test Facilities

Very shortly after induction relays began to be installed on switchboards there arose a need for a quick and safe way of testing relays and other switchboard instruments without taking high-voltage equipment out of service, without interfering with the operation of the power system, and without removing the protection any longer than absolutely necessary. Various types of test switches, test studs, test jacks and other devices have been used. Any of them are well worth while, but there is a great difference between the various types of such equipment.

Methods of Testing Ground Relays

Although the connections to plain ground relays can be checked with an ammeter, the use of balanced relays, directional ground relays, etc., makes some more elaborate check of connections necessary. Oftentimes the engineering department will spend considerable time in checking detailed wiring diagrams and attempting to lay out the wiring diagram so that directional relays will be correctly phased when installed. This may save the construction department some time if the drafting room work and construction work is carefully done. However, there is always a doubt as to correctness of the connections until it is definitely proven by the operation of the relays. More reliable results can be obtained by either phantom or staged tests.

3. *Selective Relay System of the 66-Kv. Ring of the Duquesne Light Company*, by H. P. Sleeper, A. I. E. E. Trans., Vol. 42, p. 513.

4. *Ground Relay Protection for Transmission Systems*, by G. B. Dodds and B. M. Jones, A. I. E. E. Trans., Vol. 46, p. 847.

5. "Field Testing of Relays," by W. M. Evans and R. J. Salsbury, *Electrical World*, March 17, 1928.

6. "Direct Benefits of Field Testing of Relays," by B. M. Jones, *Electrical World*, May 5, 1928.

A number of years ago the company with which the writers are connected established the practise of checking bushing current transformers, relays, etc., by phantom tests which consisted in clearing the equipment and putting low-voltage test current through it. Originally, sign lighting transformers were used for supplying this current, but special transformers were later bought which were much more flexible and with which currents as high as 1000 amperes could be obtained. This method has been in successful operation for two years.

In phasing directional ground relays by such tests, it is necessary to put test current through the breaker and also through the current transformer in the neutral ground lead. A careful check of all connections is necessary to be sure that the test current is in the proper relative direction in the breaker and in the neutral current transformer. Such tests have been very valuable in phasing relays and checking the breakdown of bushing current transformers, particularly in cases where the transformers were of poor design or the relay burden in the neutral was large. In some cases, we have found the bushing current transformer ratio to ground current was as much as 150 per cent of that to phase current. The data so obtained have been most valuable in obtaining necessary selectivity and coordination of settings.

These phantom tests have been very useful and are still being made on practically all directional ground installations as a check of current transformer ratios, connections, etc. Possibility of mistakes in test connections, the chances of a reversal of current in the transformer neutral in normal operation and other such factors make an actual staged test at normal voltage the most satisfactory check. These tests were begun on this system about four years ago and several hundred such tests both phase-to-ground and phase-to-phase have been made.

Staged tests at normal voltage are made if possible with two breakers in series and with reduced generation or with a switching setup such that the currents obtained are far below the breaker capacity. It is significant that such a large number of short circuits and grounds can be placed on a system with practically no damage to equipment and without serious effect on system load.

Some of the many benefits obtained from these tests are given below.

1. An over-all check is obtained of the correctness of relay wiring and phasing.
2. Any unsuspected characteristics of relays may be discovered by watching their operation under actual fault conditions.
3. The test results furnish a check on the method of calculating fault current.
4. By such tests may be found any unusual distribution or direction of current flow. The tests have explained several supposedly wrong relay operations by

discovery of new factors which made necessary a change of relay application.

5. Valuable data have been obtained on the effects of arcs on conductors and the consequent necessity for clearing troubles quickly.

6. Many data have been secured on arc and ground resistance. Results so far indicate that these factors may reduce the amount of ground current on distribution lines but apparently do not materially affect relay settings or fault power factor on high voltage lines.

7. The tests have shown that distribution lines may stay in trees with hazard to linemen for considerable time and not take enough ground current to operate the most sensitive ground relays now available.

8. The tests have been used to check the ability of station ground systems to carry sustained ground current.

9. Tests have indicated that a ground chain on a high voltage line does not give adequate protection to workmen if a line is accidently energized.

10. Such tests have been used to determine the performance of various types of insulators under heavy arcs.

11. One of the greatest benefits has been an increase in the morale and efficiency of the dispatching organization. The dispatchers have been present on many tests and become familiar with relay performance, possible troubles, test procedure, etc., and are therefore much better qualified to handle system troubles.

Operation of Special Relay Schemes

The tabulation herewith shows the operating record of the various relay schemes previously described. This record includes all the installations of the special schemes but includes only two of the many installations of plain directional ground relays.

The incorrect operations for scheme two are due to the following causes. Incorrect connection of the relays caused four incorrect operations, all when the equipment was first installed. Two operations were due to a relay being grounded when the substation was flooded to a depth of several feet. There was one case of bus trouble which caused an incorrect operation, as this scheme does not cover bus protection. There was another case of tripping on through trouble on the 66-kv. system which ties to the 110-kv. system through low-reactance auto-transformers. This scheme does not automatically take care of such a situation, and the settings on the 66-kv. system had to be changed. One incorrect operation was due to a mistake by a relay test man. One operation was due to unusual operating conditions which the scheme was not designed to meet. This particular condition was unnecessary and would not have been used if the relay scheme had been better known by the load dispatcher. One incorrect operation was due to inadequate system planning, as a 150-mile section of transmission line was not provided with a breaker, and the ground current at the far end was too low to operate any relay.

Four incorrect operations of Scheme 4 were due to defective relays. Scale from the magnet lodged between the magnet and the disk, binding the relay disk. Two incorrect operations were due to poor relay settings and three to mistakes on the part of the relay men.

Six incorrect operations of Scheme 7 were due to incorrect relay connections, one to a mistake by a relay test man, one to unnecessary operating conditions, and two to poor system planning.

One incorrect operation of Scheme 9 was due to a mistake in phasing while installing relays. The second

Figure	Scheme	Station	Voltage	Months in service	Correct operations	Incorrect operations
1	Directional ground	Ocoee No. 1	66,000	37	136	12
1	Directional ground	Great Falls	44,000	10	37	0
2	Cross connected directional ground	Washington	110,000	20	101	3
2	Cross connected directional ground	Arlington	110,000	4	28	1
2	Cross connected directional ground	Great Falls	110,000	5	18	5
2	Cross connected directional ground	Ridgedale	44,000	13	8	0
2	Cross connected directional ground	Ocoee No. 1	110,000	12	43	2
3	Directional ground for auto transformers	W. Nashville	154,000	5	6	0
4	Balanced ground for auto transformers	Lenoir City	110,000	16	132	9
5	Directional ground bus protection	Ridgedale	110,000	3	0	0
6	Directional ground without star transformer	Carter St.	44,000	7	10	0
7	Directional ground without line breaker	Ridgedale	110,000	28	143	10
7	Directional ground without line breaker	S. Nashville	110,000	5	8	0
8	Bus protection	Great Falls	110,000	11	0	0
9	Locking relays	Ocoee No. 1	110,000	12	43	2
9	Locking relays	Ridgedale	44,000	13	8	0
12	Low side ground protection	Murfreesboro	11,000	22	66	2
12	Low side ground protection	Cleveland	11,000	12	19	1
12	Low side ground protection	Centerville	154,000	5	0	0
			Total		806	47

was due to 110-kv. bus trouble which the scheme does not protect against.

One incorrect operation of Scheme 12 was due to a defective relay and two were due to inadequate construction work.

The total incorrect operations was 47 and the correct operations 806, giving an accuracy of 94 per cent. The plain directional ground relay operation is, of course, much more accurate as there are very few chances of wrong connections or poor settings, as these relays are relatively easy to install, phase, and set correctly. It is interesting to note that nearly all of the above incorrect operations occurred during the first few months that each scheme was in operation. As soon as incorrect operations occurred staged tests were made, and these usually resulted in finding the relay trouble and clearing it permanently.

In general, incorrect operations occurring after a scheme has been in service during one lightning season are usually due to poor system planning, defective relays, flood conditions, etc., rather than to wrong connections, poor settings, or inadequate types of relays.

Conclusion

Experience seems to show that ground relay protection is almost paramount on high-voltage transmission systems. On many systems the benefits of ground protection have been extended to lower voltage lines and it is recommended that more general use of ground protection be made on systems of all voltages. Ground relay protection possesses great flexibility of application and can be adapted to the further developments in protection which will undoubtedly occur shortly. The advent of high-speed ground relaying is just around the corner. In developing the relay schemes described above considerable experimental work was done and several of them were modified following tests at system voltage. It is suggested that experimental work of this kind be encouraged on many systems to further the development of protection schemes.

Discussion

J. H. Nehler: It may be well to mention a system of ground relay protection which is being used on the Philadelphia Electric Company's 220-kv. system and on the 220-kv. interconnection with the Pennsylvania Power and Light Co. and the Public Service Electric and Gas Co. The lines are equipped at each end with instantaneous plunger type over-current relays connected in the residual circuits. These relays are given settings slightly higher than the maximum through fault ground currents which can be calculated for the various lines under any possible operating set-ups.

The operation of these relays is similar to that of the first step of the step-by-step impedance relays except that the portion of the line over which instantaneous operation is secured is not constant but varies with the system set-up. Faults occurring beyond the limit of the protection of the relay at one end of the line will fall within the limit of protection of the similar relay at the other end where instantaneous operation will result. In the case of a system solidly grounded at all relay points, the redistribution of the zero phase sequence current after the line has been opened at the distant end, is such that an increased flow of ground currents through the relay under consideration will cause it to operate. In this manner sequential tripping on ground faults at the line ends is secured exactly as in the case of parallel lines equipped with balanced ground relays.

If these relays are non-directional, it is necessary to set the relays at each end of a given line at the same value determined by the maximum through fault ground current possible in either direction. By making them directional it is possible to take advantage of a lower setting at one end of the line. This has been done by introducing the contacts of a directional element into the trip circuit. One operating coil of this element is connected into the residual circuit of the line and the other coil to a current transformer placed in the station neutral. By this means the directional action is obtained.

A high-speed ground relay of this type comprising a directional and an over-current element has been developed which has an operating time of approximately one cycle.

H. H. Spencer: In regard to the use of directional ground relays as discussed by Messrs. George and Bennett there are in general two methods of establishing the phase of the ground current in a circuit. The more common method is to use a relay energized through current transformers by the residual current in the circuit protected and the current flowing in the neutral of a grounded-Y bank of transformers located in the substation with the relays. The torque of such a relay is, therefore, determined by the vector product:

$$I_{OL} \cdot I_{OT}$$

where I_{OL} is the zero sequence current in the line and I_{OT} is the zero sequence current in the transformer. The less usual method is to use a similar relay except that instead of being energized from the current in the power transformer neutral the second winding is energized from a wye-delta potential transformer, so that the torque of the relay is dependent upon the vector product:

$$I_{OL} \cdot E_O$$

where E_O is the zero sequence voltage of the system at the point where the relays are installed.

The use of auto-transformers in place of two-winding transformers in the power banks frequently introduce a difficulty. There are two circuits for zero sequence current, one circuit involves the faulted system and the transformer, the other circuit involves the faulted system and the unfaulted system. Now if:

X_{OA} = zero sequence reactance of the unfaulted system including the equivalent reactance of the auto-transformer winding connected to it

X_{OB} = zero sequence reactance of the common portion of the transformer winding.[1]

There is a critical value of $\frac{A_{OB}}{X_{OA}}$ which will result in no current flowing in the auto-transformer neutral. This is when:

$$X_{OA} = X_{OB}\,(a - 1)$$

where a is the ratio of transformation of the auto-transformer. With a lower value of X_{OB} the current of the outer transformer neutral will actually reverse and result in a faulty operation of the relay.

It appears that the use of the other type of relay never results in these difficulties but it has the disadvantage of involving three potential transformers.

R. H. Bennett: Mr. Spencer's point regarding zero or reversed ground current in auto transformer neutral has been

1. I. H. Summers and J. B. McClure, *Progress in the Study of System Stability*, A. I. E. E. Transactions, Vol. 49, Page 132.

recognized and encountered by the writers. Fig. 5 in the paper, deals with a method by which this condition can be met using directional ground relays with two current elements. In this case a current transformer in the power transformer neutral is not used. An auto balancing transformer in the neutral of the line current transformers is used to balance out the through feed of zero sequence current leaving the zero sequence current supplied by transformer bank to polarize relay. Such a scheme has been in satisfactory operation on this system for over a year.

The directional ground relay polarized by wye delta potential transformers has been used by many companies. However, this scheme also has its objections due to variations in the power factor of the fault, and variation in power factor in cases of simultaneous faults on different phases.

Electric Power Consumption for Yard Switching

BY P. H. HATCH[1]

Member, A. I. E. E

Synopsis.—In the application of various types of locomotives to switching service, it is at times quite desirable to have data concerning the energy requirements involved. A convenient figure for expressing such requirements in relation to work done is watt hours per ton-mile.

The determination of such a figure involves certain difficulties peculiar to switching service, in that trailing loads and distances moved are continually varying.

The electrified Oak Point Yard of the New York, New Haven & Hartford Railroad in New York City offered an excellent opportunity for determining figures of watt hours per ton-mile for different kinds of switching. Accordingly two electric locomotives were equipped with the necessary instruments, and a total of 39[1]/[6] hr. of operation was observed and recorded.

The paper describes in some detail the entire procedure of the tests and lists in tabulated form the data obtained.

Basic figures necessary for calculating watt hours per ton-mile, it was found, could be expanded to give a much broader scope to the results, so that many interesting data became available. Incidentally, the data will permit of even further expansion where certain special figures or factors are desired.

Although electric locomotives of different types were used, the results set forth in the paper should be considered without regard to either type.

It is hoped that data concerning switching operations on other railroads may become available.

* * * * *

I. General

In the case of electric locomotives operating in road, passenger or freight service the problem of determining the power consumption per unit of work done has not been difficult. From one end of a given run to the other train weights undergo few, if any, changes; if they do, such changes are easily accounted for. Distances present no problems of measurement, nor do meter readings necessary for computing total energy. In other words, power consumption per unit of work done or (to use a more familiar expression) watt-hours per ton-mile, present no especial difficulties in such cases.

Where watt-hours per ton-mile are desired for switching service, however, the problem becomes radically different. This is because where the number of cars has changed from the previous move, tonnage and distance must be determined for every individual move that the switch engine makes. It takes little imagination to understand that this makes necessary the calculation of ton-miles practically every time the switcher moves; the frequency of such moves in a busy yard is quite apparent.

A reasonably accurate figure of watt-hours per ton-mile for switching service is of use in many ways. It is, for instance, helpful in figuring battery capacity necessary for a storage battery switching locomotive, where the switching service to be handled by the locomotive is known. Also in the case of the oil or gasoline electric switcher, some idea of fuel quantities necessary for a given service may be obtained. Similarly in the case of applying an electric switcher to a particular location, advance information relative to power requirements can be determined. Still another side of the matter is disclosed when it is considered that watt-hours per ton-mile for a given locomotive in a given service may be taken as an approximate index of performance. Other uses of the watt-hours per ton-mile figure for switching service are readily possible.

It should be emphasized at this point that the tests herein described had for their primary object the determination of energy consumption (based on a sufficient number of hours of service) in terms of watt-hours per ton-mile for various classes of yard switching, without regard to type or types of electric locomotives used.

II. Description of Test and Apparatus

In order to arrive at definite facts regarding the power consumption per ton-mile for electric switching locomotives, a series of tests was run in the Oak Point Yard of the New York, New Haven and Hartford Railroad in New York City. This yard is devoted primarily to classification work in connection with the interchange business with the Erie, Lehigh Valley, Central New Jersey and Lackawanna Railroads, such business being carried on between the various harbor terminals by means of car floats. There are in general, therefore, two distinct kinds of service performed by the switching locomotives in Oak Point Yard, namely, float loading and unloading and general switching and classifying.

Oak Point Yard is roughly Y-shaped. The foot of the Y is at the north end, the south end branching out to serve the eight float bridges, together with various shop and yard tracks between the farthest bridge track on the east and the six-track Harlem River Branch on the west. Fig. 1 gives a general view of the mid-section of the yard looking south.

The switching locomotives operating in this yard have varied duties. No one locomotive is assigned to a definitive class of work. Classifying, float pulling and loading, switching the shop tracks, pushing outgoing trains, etc., are some of the services each engine may be called upon to perform.

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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For the purposes of the test, it was decided to equip a locomotive with the necessary test instruments and then have the engine put into normal service, neglecting the test entirely so far as the engine and crew were concerned. It was thought that this would give the most comprehensive results for the test, as well as burden the yard forces and engine crews as little as possible. To the men running the test was left the classification of results according to service.

For measuring watt-hours, the regular locomotive

Fig. 1—General View of Oak Point Yard

(Note curved classifying tracks at left)

watt-hour meter was utilized. It was calibrated both before and after the test. For determining distances moved, a magnetic counter was used in conjunction with dry cells and a contact-making device mounted in

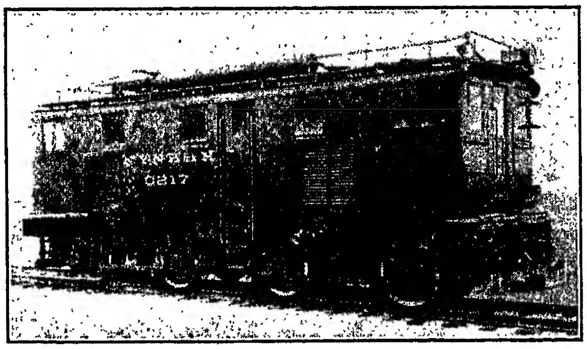

Fig. 2—Electric Switching Locomotive Used in Oak Point Yard

the end of one of the locomotive axles. From readings of the counter the number of revolutions of the wheel was determined, from which were calculated the distances moved.

The contact-making device was home-made, consisting of an automobile timer fitted with a special flange for attaching to the axle hub. Throughout the period of the test, this device functioned satisfactorily and made possible very accurate distance determinations.

The test was run in two periods of three days each. Two different locomotives were used, one for each period. The same test procedures were followed and much the same classes of work were performed by each. Each locomotive operated from the 11,000-volt a-c. single-phase supply. Specifications for the two locomotives follow:

106-Ton Electric Switching Locomotive

Classification	B + B
Energy supply	11,000-volt, 25-cycle, single-phase, a-c.
Type of conductor	Overhead
Total weight of locomotive	211,500 lb.
Total weight on drivers	211,500 lb.
No. of driving wheels	4
Diameter of driving wheels	42 in.
Total wheel base	25 ft. 0 in.
Rigid wheel base	8 ft. 3 in.
Length over coupler faces	38 ft. 3 in.
Height over pantagraph locked down	14 ft. 8 in.
No. of motors	4
Type of motors	D-c. series (d-c. from motor-generator set)
Drive	Gear
Gear ratio	17:72
Tractive effort, hourly rating	23,200 lb.
Speed at hourly rating	8.1 mi. per hr.
Tractive effort, continuous rating	14,500 lb.
Speed at continuous rating	11.4 mi. per hr.

90-Ton Electric Switching Locomotive

Classification	B + B
Energy supply	11,000-volt, 25-cycle, single-phase, a-c.
Type of conductor	Overhead
Total weight of locomotive	181,000 lb.
Total weight on drivers	181,000 lb.
No. of driving wheels	4
Diameter of driving wheels	63 in.
Total wheel base	23 ft. 6 in.
Rigid wheel base	7 ft. 0 in.
Length over coupler faces	39 ft. 1⅛ in.
Height over pantagraph locked down	14 ft. 3⅞ in.
No. of motors	4
Type of motors	A-c. commutator type series
Drive	Gear quill
Gear ratio	17:101
Tractive effort, hourly rating	23,200 lb.
Speed at hourly rating	8.1 mi. per hr.
Tractive effort, continuous rating	14,500 lb.
Speed at continuous rating	11.4 mi. per hr.

Weather and rail conditions were good for the greater part of the time in each period. A little rain was experienced in both. Average summer temperatures prevailed.

The personnel of the test consisted of three men. One rode continuously in the cab of the locomotive, and read the watt-hour meter and revolution counter; one was on the ground recording car numbers for each move; the third assisted in this work, obtained car weights from the various sources, endeavored to discover in advance the moves to be made and generally kept track of the test as a whole.

The degree of coordination and sign reading that the man in the cab and the ground man developed between them was remarkable, and resulted in 95 per cent of the

test data taken by the two in widely separated locations being capable of matching up afterward.

Getting the car numbers for each move necessary in loading or unloading a car float presented no particular difficulties after the first two or three floats had been handled. When doing yard switching or classifying, the problem was considerably more complicated; unless the ground man could see both the locomotive and the cars which were picked up or dropped, it was very difficult to coordinate distance readings with number of cars moved. Fortunately the greater part of the classification work was performed on curved track, which made relatively easy the coordination of moves between the ground man and cab man.

It may be of interest to follow the procedure for "shaking out" a string of cars, and to note the method for keeping track of the number of cars and distance each combination moved during the process.

Let it be assumed that the locomotive has "hooked on" to a string of cars, which it will proceed to classify

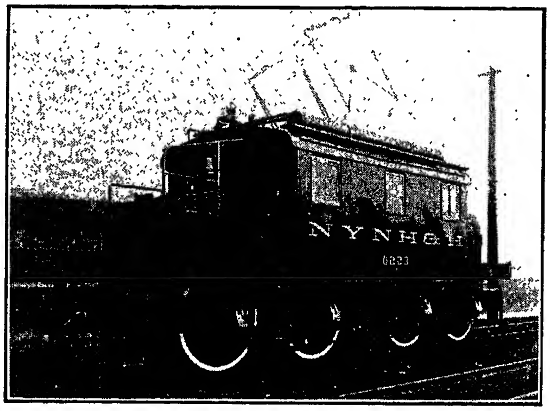

FIG. 3—ELECTRIC SWITCHING LOCOMOTIVE USED IN OAK POINT YARD

on the different yard tracks according to destination. Classifying in general is done on a fan-shaped set of tracks. The string of cars is hauled out on the lead track and the proper switches thrown. Then a rapid acceleration is made toward the branch tracks. When sufficient speed has been attained, the first cut is made; that is, for instance, three cars bound for track 7 are uncoupled and allowed to coast down to their allotted track, the rest of the string of cars and the locomotive being brought to a stand-still and returning to the lead track. The same procedure is followed until all the cars in the string have been placed on their respective tracks.

In practise, the moves are made as rapidly as the cars can be "kicked off," with the accompanying starts and stops necessary.

The test procedure called for the ground man obtaining in order, the numbers of the cars in the string. Then, standing near the middle of the curve (as previously mentioned the classifying lead tracks are on a curve), he was able to signal to the man in the cab when a new move started and also to determine how many cars were kicked off at a time, so checking off their numbers in his record book.

Following is a sample set of classification moves, taken directly and without change from the notebook of the ground man. As noted, each move was assigned a number, such as A-9, C-6, H-8, etc. The car numbers are noted and the general procedure for getting the tonnage and distance moved during classification moves can easily be deduced, when it is remembered that distance was read at the beginning and end of each numbered move. "X" denotes an empty car.

H-1	Light		
H-2	2—Reachers		
H-3	Light		
H-4	CNJ	60248	18 cars
	CNJ	62614	
	CNJ	62874	
	CNJ	64535	
	CNJ	64737	
	NH	51943 X	
	NH	52137 X	
	NH	55065 X	
	NH	54150 X	
	BIG 4	41120	
	BIG 4	58904	
	B & M	49472	
	SO.	134985	
	CNJ	61146	
	CNJ	61728	
	CNJ	65130	
	CNJ	50445	
	CNJ	61818	
H-5	H-4 less last 2 cars		16 cars
H-6	H-4 less last 3 cars		15 cars
H-7	H-4 less last 6 cars		12 cars
H-8	1st 11 cars of H-4		
H-9	1st 9 cars of H-4		
H-10	1st 8 cars of H-4		
H-11	1st 5 cars of H-4		
H-12	1st 4 cars of H-4		
H-13	1st 3 cars of H-4		
H-14	1st 2 cars of H-4		

Translating the above: The locomotive made move H-1 light; coupled on to flat cars used as reachers for float work and moved them to another track (H-2); returned light (H-3) to the string of 18 cars to be classified. These 18 cars were moved to the lead track, stopped, reversed and two cars kicked off (H-4); this left 16 cars for the next move; these 16 cars were moved back to the lead track, stopped, reversed and one car kicked off (H-5); the 15 cars remaining were handled similarly for move (H-6) and three cars kicked off; twelve cars now remained, which were handled as before and one car kicked off (H-7) leaving the first eleven of the string. These were handled similarly, kicking off two cars (H-8), then one car (H-9), then three cars (H-10), then one car (H-11), then one car (H-12), again one car (H-13), which brings us to the last move (H-14) where the last two cars were moved to the lead

track stopped, reversed, and kicked off to a classification track.

III. Analysis of Test Conditions

The test was of necessity subject to certain errors. Regular engines on their regular runs were used and regular procedures as to switching were followed all through, with the possible exception that the work of the engine under test was not varied quite as much as usual. This did nothing to detract from the test as indicating actual average conditions, and did help some in separating the results according to class of service performed.

Gross weights for loaded cars were taken in round numbers as shown in the various yard records, float lists, etc. Empty car weights were taken as 20 tons. This is the figure used in making up train weights and may be considered as a good average for all empty cars.

Distance readings were accurate to lengths less than

Fig. 4—Electric Locomotive in Float Service—Oak Point Yard

View showing locomotive, reacher cars, and float bridge. Note incline of bridge apron

the circumferences of the driving wheels to which the revolution counter was attached. These circumferences for the two locomotives used were 16½ ft. and 11 ft. Slipping of the drivers to the axle of which the revolution counter was attached was a potential source of error; fortunately, practically no slipping of these particular wheels on the locomotives was noted. (On both locomotives, all axles are driving axles.)

It was first intended to read the locomotive watt-hour meter for each move; this was impossible, however, as the meter, being the regular locomotive type, did not register enough for accurate reading in the case of the shorter moves. The meter readings, therefore, were confined to changes in classes of service, or to other sufficiently long intervals, to insure accurate data.

The meters on both locomotives were calibrated before and after the tests and were accurate to within 1 per cent during the tests. A certain inaccuracy in scheme of meter connections was present; this, however, was considered within the accuracy limits of the tests as a whole.

In any given move where a car or several cars were kicked off, the move with the number of cars as at the start was considered to terminate when the locomotive with its remaining cars had been brought to a standstill. This did not involve great inaccuracy, as the only energy not taken account of was that required to brake the kicked-off cars. In comparison with the energy required for acceleration of the string, this is practically negligible.

Where the locomotive and its load made short moves of less than a car length or two, no record was made. The only effect of this was to increase the watthours per ton-mile figures very slightly.

The test locomotives were in several instances used to push out road freight trains from the yards. The time that the engines first hooked on the rear end until the push-out was completed was deleted from the records of the test. The time spent in returning from the pushing and in traveling to the train to be pushed, was counted, however, as being properly classified as switching service.

In the tabulated summaries for the first period and for the test as a whole, a certain discrepancy may be noted in that the sum of the number of moves, miles, ton-miles, etc., for the different classes of service does not equal the total figures for the entire period or periods. The latter figures take into account five moves totaling 426 ton-miles which were omitted from the records of classes of service as not belonging specifically to either, yet properly belonging to switching service.

As a matter of interest, average speeds for elapsed time for each day were calculated. These took into account the 20-min. lunch period per shift, but omitted time consumed in pushing trains or doing other work of a non-switching variety.

When a rate of energy consumption with respect to work performed is desired, there are two methods of obtaining the final result. In the particular case under discussion, the watt-hours per ton-mile could be calculated for each move and an average taken for as many moves as constitute a certain period or class of service. The other method consists of taking the sum of the ton-miles for a given series of moves and dividing this figure into the sum of the watt-hours for these moves. It was thought the latter method gives the more representative results over a given period, is more accurate, and, as previously pointed out, lends itself more readily to the test procedure as regards meter readings.

In final figures of watt-hours per ton-mile, decimal points are omitted, inasmuch as the accuracy of the test as a whole would not make them particularly significant.

IV. Tabulations

The tabulations of data obtained in the test show

results for each period, for each class of service, and a composite summary for both periods.

V. Analysis of Results

Inasmuch as yard switching operations are continually changing—no two days being alike—no unfavorable comparisons are justified as between the locomotives used in the first and second periods. Nor is any comparison intended, as there are too many variables encountered in two three-day periods a month apart to make such a comparison at all significant. The differences which do exist in the results of the two periods serve to illustrate the fact that many hours of switching service must be recorded before a representative figure for watt-hours per ton-mile can be obtained, regardless of the type of locomotive used.

Although figures of watt-hours per ton-mile for the various services were primarily desired, it is interesting to note the extent of the data obtained from basic records of kilowatthours, number of cars, tons, and distances moved.

For purposes of discussion, the first three days of the test in July are referred to as the first period; the second three days of the test in August are referred to as the second period.

In general, each period was similar in classes of service performed, with the exception that the second included considerably more float unloading or "pulling." Comparison of the figures will show that float unloading is the highest in power consumption per ton-mile.

This is no doubt due to the incline of the float bridge apron at low tide, a great number of small moves and considerable waiting time. During the tests, the apron incline was for the most part against movements from the float. At high tide this incline is reversed, but not to the same extent as at low tide. The number of small moves comes in the fact that the floats must be loaded or unloaded in parts; when unloading, the parts are additive; that is, each succeeding move is with a greater tonnage; (in loading, on the other hand, each succeeding move is with a decreasing tonnage). It can readily be understood, therefore, that a low tide will definitely tend to increase the energy consumption for float unloading. Waiting time is another factor which enters into the situation; a certain stipulated time is allowed for unloading, loading, and releasing a car float. Hence a switcher is often dispatched to a float bridge to wait for an approaching float. If the stand-by losses of the locomotive are relatively great, the watt-hours per ton-mile for float unloading are correspondingly increased.

The tests under consideration showed that the general impression that float service is a more severe variety of switching than classifying is in the main correct, though local and tidal conditions may vary this somewhat.

THE NEW YORK, NEW HAVEN AND HARTFORD RAILROAD

Electric Power Consumption for Yard Switching

Condensed Summary—Oak Point Yard, New York

Period of Service	No. of moves	Mileage	Avg. speed (m. p. h.)	Car miles	Trailing ton-miles	Total ton-miles	Trailing tons per move	Kw-hr.	Kw-hr. per mile	Watt-hr. per car mile	Watt-hr. per trailing ton-mile	Watt-hr. per total ton-mile
First Period, July 25-27, 1928												
July 25, 1928, 6 hr.	110	19.03	3.13	169.4	4180	5901	214	527	27.7	3111	126	89
July 26, 1928, 6 hr.	91	17.11	2.81	149.9	5441	6987	330	525	30.7	3502	97	75
July 27, 1928, 7 hr.	129	22.71	3.28	193.4	7858	9914	321	711	31.3	3676	91	72
Three-day period, 19 hr.	330	58.85	3.08	512.7	17479	22802	288	1763	30.0	3439	101	77
Yard classifying	267	47.17	——	427.0	14833	19102	292	1480	31.4	3466	100	77
Loading car floats	32	5.88	——	45.6	1215	1 746	244	131	22.3	2873	108	75
Unloading car floats	26	4.37	——	29.0	1133	1528	337	130	29.8	4483	115	85
Both loading and unloading car floats	58	10.25	——	74.6	2348	3274	286	261	25.5	3500	111	80
Second Period, August 13-15, 1928												
Aug. 13, 1928, 3 2/3 hr.	113	13.76	3.73	76.8	4070	5528	314	573	41.7	7457	141	104
Aug. 14, 1928, 8 1/2 hr.	115	21.63	2.55	164.2	5184	7477	269	1030	47.6	6272	199	138
Aug. 15, 1928, 8 hr.	134	24.55	3.08	202.8	8314	10966	370	1131	46.1	5576	136	103
Three-day period, 20 1/6 hr.	362	59.94	2.99	443.9	17568	23971	320	2734	45.6	6159	156	114
Yard classifying	277	42.93	——	322.6	13990	18591	333	1950	45.4	6045	139	105
Loading car floats	25	7.14	——	52.7	1207	1964	234	249	34.9	4728	206	127
Unloading car floats	60	9.86	——	68.6	2371	3416	299	535	54.2	7794	226	157
Both loading and unloading car floats	85	17.00	——	121.3	3578	5380	280	784	46.1	6364	219	146
Both Periods, July 25-27 and August 13-15, 1928												
Six-day period, 39 1/6 hr.	692	118.79	3.03	956.6	35047	46773	305	4497	37.9	4699	128	96
Yard classifying	544	90.10	——	749.6	28823	37693	313	3430	38.0	4575	119	91
Loading car floats	57	13.02	——	98.3	2422	3710	240	380	29.2	3865	157	102
Unloading car floats	86	14.23	——	97.6	3504	4944	310	665	46.6	6810	189	135
Both loading and unloading car floats	143	27.25	——	195.9	5926	8654	282	1045	38.4	5332	176	121

General yard switching and classification work showed reasonable figures for power consumption per ton-mile. Such figures would, no doubt, vary for different yards, since grades and curves in no two yards would be alike. But Oak Point Yard is large enough so the figures indicated give what is considered a good average figure for flat yard switching. In this connection, it would be extremely interesting if a comparison of watt-hours per ton-mile for flat switching and hump switching could be obtained. Figures for the latter type of switching, of course, should not be considered without due reference to the gradients of the hump approaches.

It will be noted that the figures of watt-hours per ton-mile for each period show a decided difference. This is undoubtedly due in part to the difference in types of locomotives used as regards stand-by losses. Another factor tending to increase this difference between the two periods was that the second included more float work, particularly unloading. Undoubtedly other variables such as different rates of acceleration, different proportions of power-on and power-off time, etc., were present and had their part in the difference noted.

VI. Conclusion

As previously remarked, extreme accuracy was more or less impossible of attainment under the conditions of the test. Regular operating procedures were followed as closely as possible, as it was considered the results thus obtained would show average every-day conditions and would be of greater value than if laboratory precision of measurements were undertaken at the expense of the test as a whole.

To obtain two three-day periods of switching service exactly alike is well-nigh impossible. In spite of the general similarity of service for the two periods under discussion, there were certain differences between the two which make undesirable any conclusions regarding the types of switching locomotives used. Where comparisons are mentioned, they are simply for explanation of test results, and are not to be considered as reflecting upon either type of locomotive.

It is believed, therefore, that the data herein set forth, represent actual, average conditions of switching service in Oak Point Yard. The various figures obtained for electric power consumption in watt-hours per ton-mile, it is thought, are well within the accuracy range of existing freight car loaded and light tonnage figures. It is felt that an important object will have been gained if this study may lead to similar tests being made under different conditions on other railroads.

In conclusion, thanks are due to all those participating in, or arranging for, the tests. Particular mention is due Mr. W. T. Kelley, Asst. Engineer, and Mr. E. S. McConnell, Mechanical Inspector, for their very able assistance in the running of the test and calculation of results; to the Oak Point Yard forces under Messrs. E. J. Cotter and John Dunford, Assistant Superintendent and Yard Master respectively, for their excellent cooperation; also to Mr. S. Withington, Electrical Engineer, and Mr. A. L. Ralston, Mechanical Superintendent, for their encouragement, and criticism of results.

Control Systems for Oil and Gasoline Electric Locomotives and Cars

BY N. L. FREEMAN[1]

Associate, A. I. E. E.

Synopsis:—A review is given of the development of self-propelled railway vehicles which utilize electrical transmission, paying particular attention to the ways and means of regulating the torque demand on the internal combustion engine which serves as the source of power, and the supply of power to the auxiliaries.

Two general designs are discussed, and classified as "differential field control" and "torque control." In differentiating between these two systems, two types of differential field control are outlined, giving their major advantages and limitations. The principle of torque control depending upon constant engine speed is discussed, enumerating its advantages over previous schemes. It permits the absorption of the entire engine output for any throttle opening and engine speed selected. The various relays and control devices necessary for proper operation of the scheme are described, together with the use of the auxiliary generator and main generator for compressor operation and battery charging.

The appendixes deal with the design of auxiliary generators for differential field control and a short description of the method of limiting the torque required by means of a torque regulator and contactor. The problem of overcoming hunting of the system due to lagging of the field change and its solution are given.

The differential field control comprises the minimum amount of apparatus consistent with operation of the car or locomotive and its auxiliaries. It should be noted, however, in connection with this type of control, that battery charging and air compressor operation cannot be obtained at both operating and idling speeds of the engine.

Torque control equipment functions to vary automatically the generator voltage inversely as the current in such a way that the full available power of the engine is utilized; it acts directly on the generator field and has proved its superiority over methods of regulation involving the exciter field. The availability of the auxiliary generator for compressor operation and battery charging, when the engine is running under load, represents a marked advance in design. The main generator supplies these auxiliaries during idling. The torque control system meets the requirement of any type of engine.

* * * * *

INTRODUCTION

SELF-PROPELLED railway vehicles driven by internal combustion engines have a brief history of about 30 years. Those using electrical transmission outnumber all other types. The major portion of their development has been crowded into the period beginning with the year 1924. In this short time, this branch of transportation has grown from a group of low powered gasoline-electric rail cars to embrace many classes of gasoline and oil cars and locomotives with highly effective electrical transmissions.

From the beginning, the electrical transmission for commercial railway vehicles has included a generator and traction motors. Practically all the traction motors have been of the series type, the input to such motors being a function of speed and applied voltage. As overloading an internal combustion engine will cause it to run at a lower speed or stop it entirely, it was necessary to protect against such a condition. In 1924 and 1925 this was done by means of a differential field for reducing the main generator voltage with an increase in current demand. The differential field was placed on the exciter because it produced more favorable characteristics and was a much less expensive winding.

There were two distinct methods of applying this differential winding. One designer distributed the winding to all poles in the exciter and proceeded to charge the battery from the exciter through a field on the main generator. This system supplied the usual drooping characteristic with fairly sharp voltage regulation with respect to engine speed. (See Fig. 1A.) Another designer concentrated the differential winding on two of the exciter's poles. The battery was charged from the exciter, but through an external resistor instead of a field. This concentration of winding gave more than the usual drooping characteristic. Its power requirement was much more uniform over the range of car speeds with less sharp regulation with respect to engine speed. (Fig. 1B.) Both systems were widely used and are still being applied with design improvements. They are more completely discussed in Appendix I.

In all of these equipments, the auxiliaries presented a serious problem. The auxiliaries are the sources of brake air supply, lights, battery charge, and radiator air supply. The brake air supply has been obtained from an electrically driven compressor in the majority of cases. The battery has nearly always been charged from the exciter or its equivalent. The air for the radiator has been supplied by various devices, but the chief source has been an electrically driven fan. Since the auxiliaries were operated from the main generator, their operation was dependent on the engine and car speed simultaneously, and the results were none too satisfactory. This was particularly true when the profile contained grades which required slow, steady pulling in one direction and a long drift in the other. Battery charge and air supply offered the most serious problems under these conditions.

In order to improve the operation of auxiliaries and the loading characteristic in general, a system of torque control was introduced. The equipment using this system had its loading characteristic controlled by a regulator which varied the main generator field.

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

30-112

This regulator limited the torque load impressed on the engine to a selected value. The regulator spring had a simple hand lever adjustment for selecting the torque required. In this scheme the exciter became an auxiliary generator and supplied a battery charge under almost any loading condition. A low-voltage compressor operated from this source and, in addition, the battery and compressor were supplied current through the starting connections from the main generator

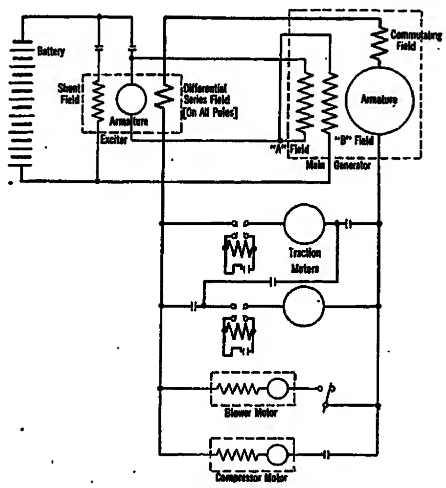

FIG. 1A—DIFFERENTIAL EXCITER SCHEME OF CONTROL, USING A DISTRIBUTED DIFFERENTIAL WINDING ON THE EXCITER AND THE "B" FIELD ON THE MAIN GENERATOR

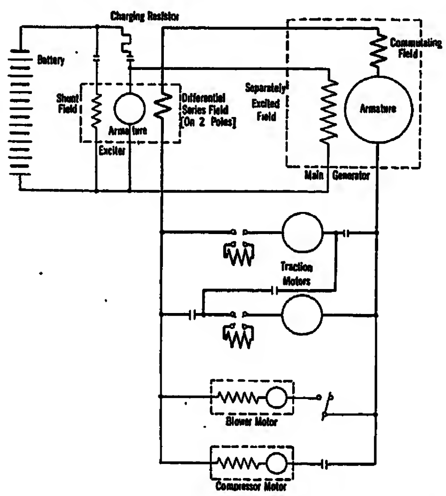

FIG. 1B—DIFFERENTIAL EXCITER SCHEME OF CONTROL, USING A DIFFERENTIAL FIELD CONCENTRATED ON TWO POLES OF THE EXCITER

during idling. This equipment was arranged to use the main generator as a starting motor. All of this is shown in Fig. 2. This equipment with its definite and effective loading characteristic overcame many of the early problems. It was especially effective with the more rugged profiles and irregular schedules and removed several of the natural handicaps under which these cars and locomotives formerly operated.

REQUIRED FUNDAMENTALS

The success of the torque control system led to further improvements which enabled it to automatically cope with variation in the engine output characteristic due to innumerable factors encountered in service. These factors can be classified in general as fuel, mechanical, and atmospheric[2] differences.

Fig. 3 shows a test curve of one engine with respect to its rating. This particular make of engine has been

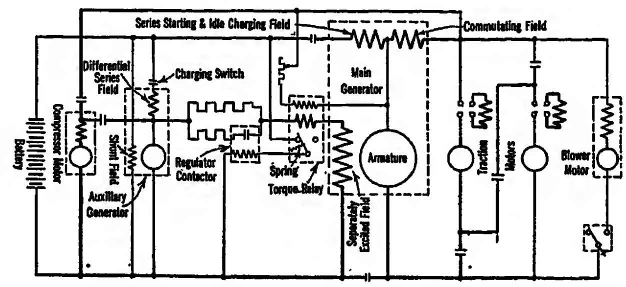

FIG. 2—EXTERNAL REGULATOR SCHEME OF CONTROL, LIMITED TORQUE SYSTEM

very dependable in service, yet in the course of 5000 hours service its output has been known to be as low as 85 to 90 per cent of its rating. This fact, in conjunction with the curve of Fig. 3, indicates an output variation for this gasoline engine of 25 per cent to 30 per cent under service conditions. Such a condition is not peculiar to one engine but representative of internal combustion engines in general, since it is a function of the three groups of factors of variation. Similar

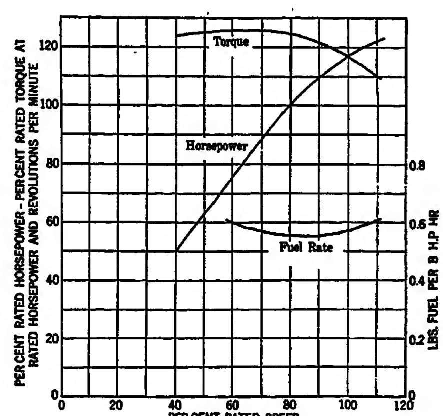

FIG. 3—A TYPICAL GASOLINE ENGINE PERFORMANCE CURVE

variations, probably of different magnitude, have been repeatedly observed with oil engines.

Engines in railway service are frequently called upon to do 2000 hr. or more of full-load duty between major overhauling periods. The total number of hours of operation is considerably greater than the hours of full-load duty for this very exacting service. Such engines

2. "Horsepower Correction for Atmospheric Humidity," by Donald B. Brooks, *S. A. E. Journal.*

are expensive and should be conserved wherever possible, which of course is true of any engine. The length of time between overhaul periods and the life of an engine both depend upon total wear of its parts. An expression of exact relationship between revolutions, load, and wear would be a complicated function. The usual index of engine life, however, is its total number of revolutions.

Obviously, the most economical method of operating an engine is to secure the desired power at the lowest speed at which the engine may be operated to develop that power.

In either an oil engine or a gas engine operating at a given speed the mechanical efficiency at its rated load is better than at lower loads. The corresponding thermal efficiency under variable load conditions in an oil engine partially compensates for the change in mechanical efficiency; while in a gas engine, the thermal efficiency drops appreciably and a severe throttling loss appears with a reduction in load.

Thus, for a gas engine, and to some extent for an oil engine, the best economy appears at the rated load for a given speed.

From definite cylinder charges certain conditions may be expected. These charges produce a torque. If there is an exactly equal opposing torque, the engine's speed will be constant. If the opposing torque is greater than the engine torque, the speed will decrease and vice versa. Obviously, either the engine torque must be matched to its load, or the load to the available engine torque. If the required engine size is to be a minimum, its revolutions conserved, and the economy kept at the most desirable value *the load must be fitted to the torque available.*

The ideal loading is that which, regardless of engine condition, will hold the engine to a selected speed. Such a system of loading permits the absorption of the entire output of an engine for any throttle opening and speed selected. That, however, is beyond the scope of performance of differential or definite characteristic machines, since the ideal loading is predicated on an engine's ability to maintain its speed.

Torque Regulation from Speed

The original method selected for measuring engine speed was to express the speed in terms of voltage from a small control generator of constant field strength. Because of the constant field strength, this voltage would then be proportional to the generator speed. The control generator was belted to the engine, making its voltage also proportional to engine speed. This voltage was then applied to a sensitive voltage relay which operated a contactor in the main generator field. The contactor gave the minimum field strength required when open and the maximum field strength when closed (See Fig. 4A). Such a system is not stable, since large power surges originate within it. Stability was obtained by recalibrating the voltage relay in step with the regulating switch. This is shown in Fig. 4C. A discussion of this method of stability appears in Appendix II.

It was but a short step from the control generator to an exciter or auxiliary generator for the combined duties of both. Since the regulation was to be for an almost

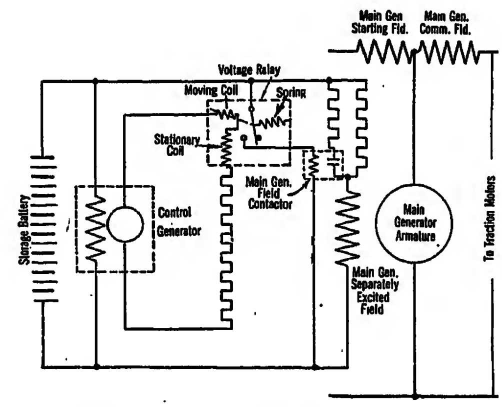

Fig. 4A—Elementary System for Regulating Torque from Speed. (This is an Unstable System)

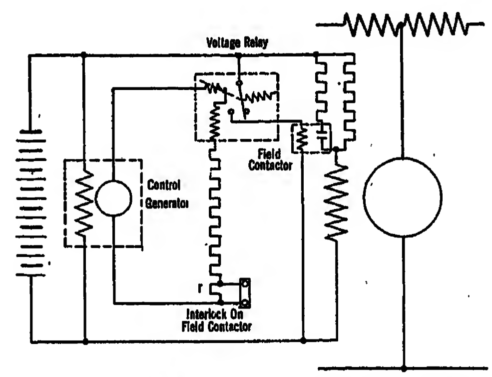

Fig. 4B—Interlock Method of Stabilizing Speed—Torque System

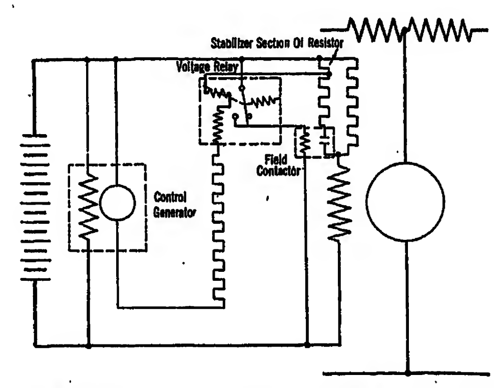

Fig. 4C—Resistor Stabilized System of Regulating Torque from Speed

constant speed, the auxiliary generator volts would be at a nearly constant value for each selected speed. By varying the speed setting over the lower engine speed range, with the resistor in series with the relay, the auxiliary loads were reduced with speed. By making the speed adjustment through the upper speed range in the auxiliary generator field the auxiliary load

was not reduced in this band with respect to engine speed. Thus the auxiliary generator volts are constant in this neighborhood. Therefore, the battery is charged through a ballast or cushion resistor. This is a tapered charging system and commonly known as the modified constant potential system of charging.

The use of this type of charging system permitted the introduction of another feature. The charging resistor is of very low value,—a fraction of an ohm. By connecting the charging switch between this resistor and the auxiliary generator, and the shunt field across the battery through this resistor as shown in Fig. 5, the field is battery-excited, while the charging switch is open. As soon as it closes, the auxiliary generator becomes shunt-excited. This feature has an important result. For all practical purposes, the system is independent of battery condition. Further, the already narrow regulation speed band is further narrowed.

This system of regulation also removes one of the objectionable features of electrical transmissions, which is that the loading characteristic of the electrical equipment changes considerably with temperature. Large temperature changes are frequently

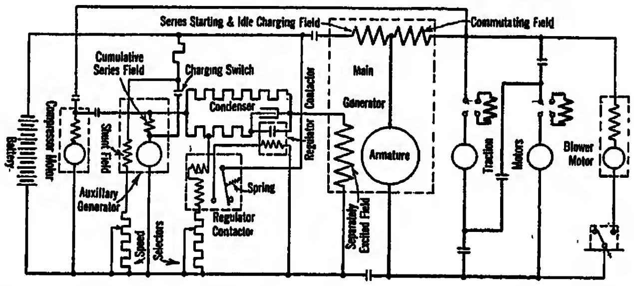

FIG. 5—EXTERNAL REGULATOR SCHEME OF CONTROL, TORQUE REGULATION FROM SPEED SYSTEM

incurred in the electrical equipment at the beginning of service operations. Resistance variation effects due to temperature are reduced in this scheme by the use of near zero temperature coefficient resistors in the two circuits where such changes would produce differences in speed settings. These two circuits are the relay circuit and the auxiliary generator field. Nearly all the heating in these circuits takes place while the engine is warming up and pumping air. In the routine of service, therefore, the effects of temperature do not appear.

The theory of torque control from speed is sound. As developed it is simple. As a result, a simple, effective scheme has been constructed which allows the operator to select the speed at which he desires to operate the engine and the control system insures the engine being effectively loaded at that speed.

EQUIPMENT OF SPECIAL SIGNIFICANCE

Two pieces of apparatus of exceptional merit were used as standard parts of this equipment. These are the "dynamic" voltage relay and the regulator contactor. The voltage relay has been thoroughly described in the May 1929 issue of the *Electric Journal*, under the title of "A Sensitive Roughneck." Briefly, it consists of a powerful magnetic circuit excited by a stationary coil, a moving coil in the air-gap, and a set of carbon contacts. The stationary and moving coils are in series. The moving element is mounted on knife edges and operates against a long camber spring in tension. Fig. 6 consists of a picture and a section of the relay.

The regulator contactor is shown in Fig. 7. It is of the conventional magnetic contactor design, except that it has two sets of silver contacts in series and no blowout.

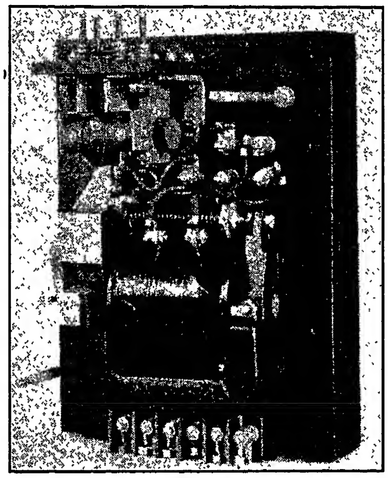

FIG. 6A—REGULATOR RELAY

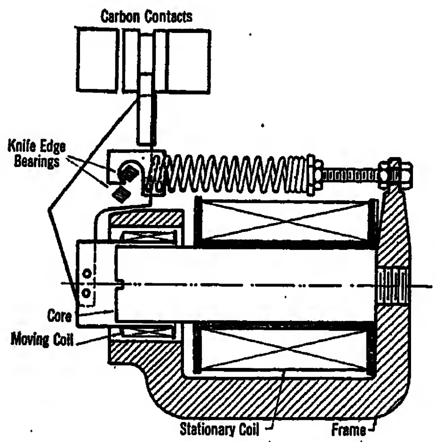

FIG. 6B—REGULATOR RELAY (SECTION)

It operates with smaller than standard contact travel, does so positively and is, in general, a very fast, sturdy switch.

The operation of this switch is assisted by a small condenser across its contacts. The condenser action momentarily short-circuits the switch at opening. While the condenser is very small with respect to the inductive load of the field, it gives the regulator contactor time enough to open with little contact load. The result is arcless interruption of the circuit. This is an application of the deion principle.

Special Features

As stated in the beginning, auxiliaries present an important problem. The constant voltage source of the auxiliary generator is almost ideal for the auxiliary power source during running. During idling, the main generator is used through the starting connections for charging the battery and operating the auxiliaries. Being charged through a differential series field, the battery regulates the main generator voltage. This provides a source of auxiliary power for the remainder of the engine operating cycle.

The lighting, control, and field loads on the battery are independent of car or locomotive speed and engine speed. In order that a battery go through a minimum number of charge and discharge cycles it is desirable to carry these loads from the charging sources as much as possible. At the same time, a continuous charge to the battery may be kept within the approved limits. These two features improve battery life, make its capacity available a greater portion of the time, and reduce the voltage fluctuations in the low-voltage circuits.

The compressor supplies air for brakes, signals, and air-operated control. Most of it is required during periods when the engine is not supplying power to the traction motors; hence, it is desirable to operate it from the charging sources.

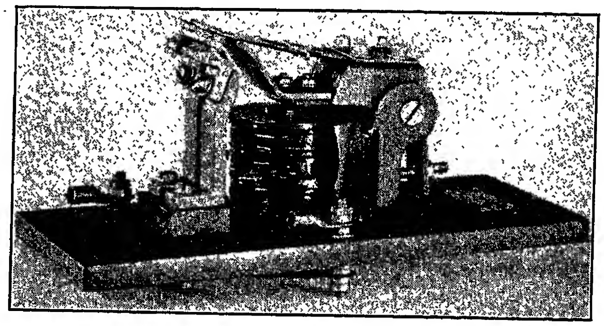

Fig. 7—Regulator Contactor

The radiator blower is needed more when the engine is delivering full power than any other time. Since the heat losses are highest at such times its operation should be in step with engine power periods. At other times natural ventilation is usually sufficient for the radiators: the radiator blower motors do not generally require a more constant supply of power than furnished by the main generator when delivering traction power.

The measuring of speed by voltage is used to eliminate severe surges in the idle charge system. This is done with the same voltage relay that controls the loading by setting it for a speed slightly above the idle speed when the controller is moved to the "off" or "idle" position. As may be seen in Fig. 6B, the relay is equipped with a moving contact that operates between two stationary contacts. In case the relay current exceeds two amperes, the moving contact is actuated in the direction opposite to the pull of the spring until it touches one of the stationary contacts. The regulator contactor is energized by the closing of the moving contact on this stationary contact. Should the relay current become less than two amperes the spring causes the moving contact to touch the other stationary contact. The circuit thus established is the one used for energizing the starting and idle charging contactors. Refer to Fig. 8, which shows this connection.

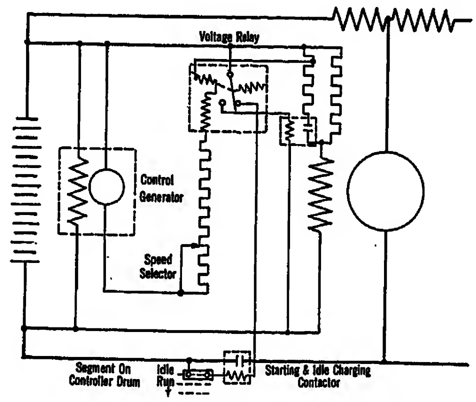

Fig. 8

In the third regulating system described, Fig. 2, a transition was developed which was distinctly one for self-propelled equipments. It is also used in the new system and is a closed transition. The operation is accomplished by opening the regulator switch, closing one parallel switch, opening the series switch and closing the other parallel switch, all in succession and followed by closing the regulator switch. This transition is made with no noticeable change in engine speed and without noticeable vehicle surges, thus indicating a continuous accelerating rate.

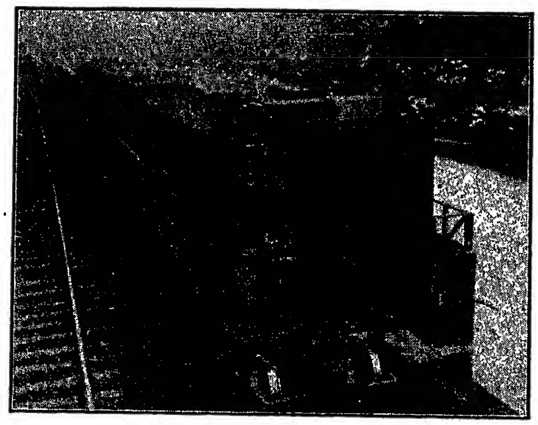

Fig. 9—Test Car

Field Tests

After this system had been well tested in the laboratory, a test car was built (Fig. 9) and equipped with a large gasoline engine, generators, control, and motors. Again the system was thoroughly studied and im-

proved as suggested by the tests. As this indicated a successful scheme, arrangements were made with the Baltimore and Ohio Railroad to equip a car with similar control. This car operated over a branch line in West Virginia, and from the beginning, the installation was a decided success. A car which was almost ready for shopping stayed in service for 50 per cent more mileage, and showed a better operating record than ever before.

The chief characteristics of the changed performance were the buoyant operation of the engine and the excellent car accelerating characteristics. With the engine loaded by this scheme, it came up to speed very promptly. There was a smooth continuous flow of power from the time the engine attained the speed selected by the operator until he shut off. There was no complicated handling needed and men unfamiliar with the new equipment had no trouble in operating and maintaining it.

Summary

Since the beginning of the history of self-propelled cars and locomotives the electrical transmission has been used extensively. All previous systems had their common and special faults. A simple system using speed as an indication of engine torque has now been developed. This system suits the torque applied to the engine to whatever torque the engine is able to develop, at a selected speed and throttle opening, regardless of the condition of the engine at that time. If one cylinder does not fire the load is decreased accordingly, but the speed remains the same. It thus enables the operator to utilize the maximum horsepower the engine can develop at any time. This is of vital importance on a car or locomotive with a limited power plant.

Additional features of continuous power supply for battery charge and compressor operation, and an improved closed transition are used. The scheme has been thoroughly tested with entirely satisfactory results.

Appendix I

There have been two types of control used extensively on self-propelled railway vehicles which have electrical transmissions. These two types have been those equipments employing differential fields to approximate the proper loading characteristics and those which used external regulators to the same end, together with improved performance in other departments of the equipment. The writer does not consider the hand-operated bus type control employed on small industrial locomotives as in comparable service with these two types of control.

There are two types of differential field control, both having the differential field winding on the exciter. One type, which is shown in Fig. 1A, has a differential winding distributed over all the exciter poles. The other has this winding concentrated on two of the exciter's six poles and is shown in Fig. 1B.

The differential type having the distributed winding uses a main generator having two windings on its main poles. One of these windings, designated as the *A* field, is connected directly across the exciter armature. The other, the *B* field, is so connected that the battery is charged through it. This accomplishes several things, among them, increasing the effect of the differential field and making the unloading due to a drop in speed much more pronounced. The change in field current and loading are due to the current through the *B* field depending upon the difference of potential existing between the exciter and the battery. An example of the regulation of volts with respect to load currents of one of these generator exciter combinations is shown in Fig. 10. The scheme is subject to the usual change of characteristic due to temperature effects. Battery condition will also affect its regulation characteristics. The usual application of this scheme has included series, parallel, and short field operation of the traction motors, so that the part of the regulation curve may be used where the loading is the best.

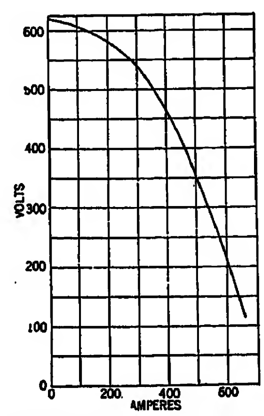

Fig. 10—Performance Curve of a Differential Exciter Equipment Using the "A" and "B" Field on the Main Generator

The differential field type which has the concentrated field on two diametrically opposite poles of the exciter is designed to obtain a good regulation curve by varying the exciter voltage which is applied directly to all the main generator field. The method of producing the required voltage from the exciter is unique. The exciter armature is wave-wound, which makes it two-circuit. The conductors of each of these two circuits are in series and appear under all six poles of the exciter. Then, with constant battery field on all six poles, all conductors produce a voltage in the same direction. The introduction of current into the differential winding on two poles reduces the over-all voltage although the excitation on the other four poles remains constant. This current may be increased to the point that the two poles bearing this winding furnish no excitation; then all the exciter voltage is generated beneath the remaining four poles. A further increase in the differential current will reverse the normal direction of flux under

the two differential poles and their action will then buck that of the other four. The flux in the two poles bearing the differential winding must follow the usual saturation curve. With an increase of current in the differential field, saturation tends to bend the lower part of the curve upward, while with a decrease in the differential current, the maximum voltage of the exciter is limited by the saturation of the two poles. The regulation of the main generator volts with respect to current is then almost hyperbolic through the working range and may be very accurately shaped by the designer to obtain uniform loading.

This equipment is also subject to a change in characteristic due to temperature effects and to some degree, battery condition. With respect to load currents Fig. 11 is a representative regulation curve of main generator volts.

The type of control which employed an external

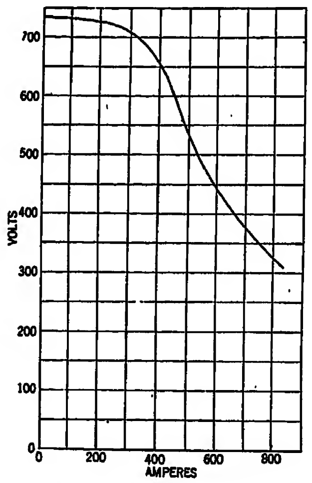

FIG. 11—PERFORMANCE CURVE OF A DIFFERENTIAL EXCITER EQUIPMENT WHICH USES A DIFFERENTIAL SERIES WINDING CONCENTRATED ON TWO POLES OF THE EXCITER

regulator did more than supply a suitable characteristic; it made that characteristic adjustable by a simple device and also simplified the problem of auxiliaries. An internal combustion engine is a producer of torque, and this regulator was arranged to limit the torque to the value that the engine would produce. This arrangement is shown in Fig. 2. The regulator was a special relay, having a field proportional to the main generator field and an armature whose current was proportional to that of the main generator armature. Its saturation characteristics were adjustable as well as the spring tension on the armature. The relay was first adjusted to the power plant and then the percentage of torque for which it was regulated was controlled by a manual adjustment of the spring tension. The relay controlled a regulating contactor, which operated between the minimum and maximum field requirements. In service, it operated in such a manner as to hold the torque imposed upon the engine constant. The torque characteristic was affected by temperature only, as the commutating field of the main generator and regulator armature heated differently under load. The regulator armature was normally shunted around the commutating field.

This external regulator system permitted the use of an auxiliary generator whose voltage was controlled by the battery through a differential field and thus supplied a low voltage for better compressor operation.

The idle charging system and the use of the main generator as a starting motor were begun with this equipment. The idle charging system also furnished power for the air compressor as required.

In general, the external regulator or torque control system was a great improvement over previous equipments. It could be simply and easily adjusted to suit the engine condition, and successful application formed a basis for further improvements.

Appendix II

A voltage relay across the control generator arranged for operating a contactor in the main generator field presents a problem. This problem is hunting. It was to be expected, since a speed change affected only the voltage of the control generator. This voltage then operated the sensitive voltage relay; next the field contactor opened or closed and the field began to change. Eventually, the field value changed enough to reverse the speed change. In all, considerable time elapsed between the registering of the chosen speed and the final reversal of the speed change causing it. This was confirmed by test. It was apparent that the time lag would need to be overcome by anticipating it, and was accomplished by changing the relay setting as soon as the field contactor closed or opened. An interlock circuit on this switch was first used for this purpose and resulted in the stabilization of the circuit. See Fig. 4B.

The introduction of this method of stabilization altered the character of the regulation, a condition which becomes apparent by considering the resistance value r as varied from zero up to higher values.

At the zero value of r, the hunting is at its worst. With each increment of r the system responds in a shorter time. Thus, the circuit operations become more and more self-energized. Such a system can be quickened to the point where it is entirely self-energized and there are no speed pulsations. For its source of energy, however, it depends on speed although it originates its own impulses.

The relation between proper time in and out for the field contactor (or main generator field strength), and the main generator load, would appear to have no connection with the regulating system. This, however, is not true, for if the average field is too low to cause adequate loading, the engine speed will increase. A slight increase in speed increases the voltage on the

control generator. The pulsating system then works between two slightly higher values. The ultimate result is that the regulator switch, or field contactor, stays closed a longer interval of time and open a smaller percentage of time. This will raise the average field value. A raise in field value will increase the loading, and hold the engine to a speed slightly higher than before. Tests have shown that the regulating band thus incurred is narrow.

An interlock on the regulator switch is not desirable. Therefore, the pulsating characteristics of the field circuit were used for the same duty. A resistor in series with the regulator switch results in less current through the switch, and is unaffected by field discharge action. (See Fig. 4c.) Consequently, a small voltage drop from this resistor was used instead of the regulator switch interlock. This again altered the pulsating characteristics of the circuit. They now depend upon two things,—the natural speed that would exist with the interlock system, and the building-up characteristics of the main field. The natural speed of closing determines approximately the time of reclosing of the field contactor, and the rate with which the field current builds up determines the time elapsing before the switch reopens. Since the field responds very slowly to such changes, the system is always exactly in step with it, yet its pulsating rate is greatly reduced. For this connection refer again to Fig. 4c.

Discussion

Hermann Lemp: Mr. Freeman's paper has proven interesting reading to me as it describes another successful way of operating internal combustion engine units with electric transmission for railway traction.

As he well states in his introduction, the year of 1924 proved the starting point of a new development; namely, the introduction of "automatic control" as distinguished from hand control.

The many gas-electric cars built before the war were all hand-controlled, and it required from ten to fourteen days instruction before an engineer could be safely entrusted with the operation of a rail car.

With the advent of what I termed "inherent automatic control," which is referred to by Mr. Freeman as "differential field control," and which was patterned to resemble the control of a steam locomotive as closely as possible, it became possible to turn over the *operation* of a rail car or locomotive to any locomotive engineer with only a brief instruction. This was so well understood that the Committee on Rail Cars of the Electric Railway Association in 1924 officially recommended its adoption.

The *inherent automatic control*, while not perfect, in its practical application to railroad service does not vary from an ideal perfect control by more than from 2 to 5 per cent, and has the great advantage of simplicity, all factors being determined when the generating unit is designed and tested. It is free from adjustable and wearing contacts, relays, delicate governor operated valves, etc. In other words, there is nothing to cause difficulty with regard to adjustment. This was attained by a centrifugal governor of an internal combustion engine acting automatically to vary the admission of fuel and the strength of the generator field.

The method of control, termed *speed control*, makes use of contacts, fluid pressure, valves, etc., and is to keep the speed of the internal combustion engine constant within narrow limits, always giving the maximum horsepower that the engine is capable of giving for the particular speed selected, or as Mr. Freeman says, "Uses speed as an indication of engine torque." It does not attempt to give a constant torque, but on the contrary, in maintaining a constant speed, uses whatever torque the engine is giving at that particular time.

In making this critical analysis the writer does not attempt to minimize the splendid development work achieved by the Westinghouse engineers, but merely wishes to point out that to call the present system a *torque control* seems to be a misnomer.

In connection with the "torque control" described by Mr. Freeman, I believe the variable engine speed settings are obtained by a fluid under pressure passing through a needle valve set at definite positions by the operator through solenoid action. Does not the viscosity of the liquid passing through a fixed opening determine the actual engine speed, and if this is a variable, such as when lubricating oil affected by temperature is used, does not the speed vary with that viscosity? I ask this question because many years ago, when I tried to govern stationary lighting sets by such a control, only water or kerosene could be used for that purpose, and I finally gave it up for centrifugal governor control.

Both the "speed control" and the so-called "torque control" make use of adjustable relays, etc., and time will prove whether it will be as reliable in railroad operation as the "inherent automatic control."

Contrasted to the above, European practise is at variance with the American. The manufacturers of Diesel engines abroad, particularly of the air injected type, objected to the running of the Diesel engines at variable speed, and hence the electrical designers use almost exclusively Ward Leonard Control. In other words, the Diesel engine is preferably run at constant speed under control of a speed governor, and the field strength of the generator is varied by hand. This arrangement furnishes to a certain extent automatic control, except that the engine can be overloaded by a careless operator, and in a Sulzer rail car I inspected this winter on the Swiss Railways *a special visual signal* is placed in front of the operator advising him when he overloads the engine. It has the advantage of giving constant speed for the auxiliary generator from which air compressor, battery charger, fan motor, etc., are operated, but it has the drawback, however, of using more fuel per ton-mile, of wearing out engine parts faster and of producing more vibration in the engine cab.

In my paper read before the Erie Section of the A. I. E. E. on March 31, 1924 (which was printed in abstract in *General Electric Review* of October, 1924) I said that for main line operation the European practise might prove the better. I have, however, changed my views based upon actual observation of locomotives and rail cars operating on both plans, and have come to the conclusion that variable engine speed is the better of the two.

Railway constructor Sueberkrueb has analyzed carefully all methods of control, and summed up his article in Z. d Y. D. I. of April 28, 1928, as follows: (I translate quotation.)

"Controls using *variable engine speed* work in the most economical way. The best characteristics are obtained by the 'Lemp Control' (meaning differential field control). This control by merely changing throttle position results in automatic, shockless, uniform change in tractive effort. At the same time this is obtained at the best engine efficiency and without the necessity of observing measuring instruments. It is also obtained at best efficiencies of generator as well as traction motors."

On the other hand the control described by Mr. Freeman offers a very nice solution of the operation of auxiliaries, particularly the air compressor and battery charging, by alternately operating them from main generator during idling speed and from auxiliary generator during full speed.

In this connection I want to mention another solution of the same problem successfully operating for about one year on a switching locomotive. The engine speed is controlled by a calibrated spring acting against a variable air pressure supplied by the operator through a standard air brake handle, in place of using a mechanical connection between operator's throttle handle and engine governor. The higher the air pressure the higher the engine speed. During idling, when the compressed air governor demands more air pressure for braking purposes, it automatically boosts the engine speed by supplying greater air pressure to control cylinder on governor. Hence, the same air compressor will work at normal speed when needed, and similarly the charging rate of battery will be maintained. This pneumatic control without definite steps furnishes any speeds from idling to full, and proves also a simple means for operating two locomotives from the same operating station on a multiple-unit control basis. A pneumatic interlock causes the engine speed to fall to zero momentarily previous to normal increase when the operator wishes to move locomotive.

For large main line locomotives it is my belief that a separate auxiliary engine unit of constant speed and a battery floating in connection with a main generator with drooping characteristics running at variable speed will prove the most satisfactory all around arrangement.

In conclusion I want to pay a tribute to the late Ward Leonard whose early work, against much opposition, has proven to be the foundation for all successful electric transmission in railroad practise, and I desire also to reiterate my appreciation of the fine engineering skill displayed, as evidenced by Mr. Freeman's paper, to bring to greater perfection the internal combustion engine locomotive and rail car, whose economical position is already accepted as a fact by the railroads.

R. D. Krape: It may be inferred from reading this paper that differential field control has become obsolete. Records of locomotive and rail car sales in the United States indicate that in 1929 not less than 85 per cent of all equipments sold used differential regulation.

Each form of control discussed has, of course, certain advantages peculiar to itself and under different conditions of operation, different types of regulation may be required. It is pertinent, however, to point out that differential field control is being used to a large extent today.

In the fourth paragraph of the synopsis of this paper, the statement is made that while differential control requires a minimum amount of equipment, battery charging and air compressor operation cannot be obtained at both operating and idling speeds of the engine. In our opinion at least 90 per cent of the oil electric locomotives in service in the United States today use differential field control and are equipped to supply air and battery charging at idling speeds of the engine. Furthermore, on the rail car, where these features are relatively less important, air and battery charging at idling with differential regulation have been successfully used. The inference may be drawn that the ability to operate the air compressor and charge the battery at idling engine speeds is peculiar to one form of control. Actually this is not the case, as pointed out above.

Any scheme of control depending upon electrical characteristics for engine loading has an inherent variation in characteristic due to temperature changes of apparatus. However these variations may be minimized in any such control scheme by proper design and correct use of materials. Any control scheme depending on mechanical characteristics for loading purposes, is unaffected by temperature variation of allied electrical equipment.

Fig. 10 illustrates the volt-ampere characteristic of a differential field exciter equipment with the *A* and *B* field on the main generator when running at constant speed. When connected to an internal combustion engine, the governor action of the engine regulates the speed to assist in maintaining the load on the engine. As the load decreases the engine increases in speed slightly, thereby permitting the generator to deliver a greater output since its output is very susceptible to a change in speed. The actual output of a generator when connected to an engine is, therefore, considerably closer to the capacity of the engine than that shown in Fig. 10. A more direct comparison between the two different types of differential control discussed might have been shown had Fig. 10 and Fig. 11 both been based on the same engine horsepower. Evidently Fig. 11 is based on an engine output much greater than that obtained under Fig. 10. With a full allowance for the effect of change in speed in each case and if based on the same size of engine, there would be little difference between the two curves over the normal working range.

It must not be overlooked that the field of application of gas-electric and oil-electric locomotives and rail cars is one where expert maintenance is not always to be obtained. It is highly important, therefore, that above all else the equipment be simple, sturdy, reliable and free from apparatus which increases slightly the theoretical engine utilization but in practise as a whole may decrease the availability of the equipment.

N. L. Freeman: Mr. Krape states that 85 per cent of the self-propelled equipment sales in 1929 were for equipments using differential control. This has little bearing on torque control since torque control is a very recent development and was in the process of being "road tested" in 1929. Torque control has many advantages, a fact which is not refuted by sales made while it was being developed. It is disappointing that Mr. Krape is not more specific concerning his figure of "90 per cent of the oil electric locomotives in service in the United States today use differential field control and are equipped to supply air and battery charging at idling speeds of the engine," particularly concerning the methods by which the battery and compressor were supplied current during idling.

The "inherent variation in characteristic due to temperature changes of apparatus" spoken of by Mr. Krape is at its worst in the differential equipments.

Mr. Krape's discussion of Figs. 10 and 11 can be answered by comparing Fig. 11 with Fig. 8 of Mr. Dodd's paper on *Electric Transmissions*. Fig. 11 is a "900 r. p. m., 400-hp." curve taken at constant speed and compares to curve *b*, Fig. 8 of Mr. Dodd's paper.

Mr. Lemp has presented a lot of very interesting information. Its substance, as well as the tone, is appreciated. He has, however, confused the torque control system with the oil governor on a well known oil engine. The torque control system is applicable to either oil or gasoline driven power plants. As far as the system is concerned, only overspeed and idle speed governors are required and the idle speed governor is not required on a gasoline engine. In either case the operator selects the desired throttle opening and engine operating speed. The torque control system functions to allow the engine to reach that speed with a light load and to prevent it exceeding speed by proper loading. In case the engine speed drops the load is dropped to permit the speed to rise. If the speed exceeds the assigned speed the load is increased to keep the speed constant.

We believe that time has already justified the use of contactors and relays on self-propelled equipments. Incidentally, there are no relays requiring recalibration as part of their maintenance in the torque control system.

Electric Transmission and Control of Power From Internal Combustion Engines for Transportation

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Member, A. I. E. E.

Synopsis.—The use of electric transmission is almost a necessity with large internal combustion power plants in transportation service. Furthermore, the interposition of the electric transmission provides a method of obtaining what is the equivalent of a wide change in gear ratio, as well as a cushioning of the characteristic power impulses of the internal combustion engine.

In adapting the internal combustion engine to this character of service there has been a number of problems, such as fitting the generator to the engine curve, the question of hand or automatic control, field control arrangements, single vs. multiple motor drive, and arrangement and operation of auxiliaries.

The use of the combination generator-battery power plant has recently received considerable attention. This application employs a battery operating in parallel with the engine generator power plant, capable of supplementing the power of the engine for short periods.

The characteristics of the engine used in transportation service must be well adapted to the duty required. These characteristics vary somewhat with the size of the unit and the control of the engine throttle is usually adapted to the particular problem in hand.

In this paper, the principal problems connected with the operation and design of complete engine generator units are discussed in detail and many typical schemes of connection are diagrammatically shown. No attempt is made to discuss the question of multiple power plant operation, although this would simply mean the addition of the necessary cross connections to operate the two power plants in parallel, unless, as is sometimes the case, the several power plants are operating independently of each other, each engine generator furnishing power to its own motors. In general, a fairly complete summary is given of the operation and design of this equipment as now used in American railway practise.

* * * * *

TRANSPORTATION service presents certain characteristic demands on the power plant equipment which differentiate it, for example, from marine or industrial service. Such features as high tractive effort required for rapid acceleration, high sustained speeds required for main line train operation, intermittent demand on the power plant required in making up trains or switching cars or any combination of them may be demanded of the same power plant. With this characteristic in view, I have attempted in the following paper to discuss electric transmission as applied to an internal combustion engine for such service, pointing out some of the problems which have come up for solution in such applications and some of the solutions which have been found acceptable.

With any form of motive power there is required some form of transmission between the prime mover and the driving wheels. With an internal combustion engine, in order to meet the requirements of transportation service, there is required a transmission that offers the possibility of what is equivalent to a change in gear ratio. The necessity for this is almost self-evident. The successive impulses in an internal combustion engine are of an explosive character marked by a wide variation between maximum and minimum pressures. For various engine speeds the average torque produced at the engine shaft is approximately uniform. On the other hand, the resistance to be overcome in transportation is due to the movement of trains which develop an approximately uniform resistance at any given speed and cannot well respond to an explosive driving force as produced in an internal combustion engine. The total train resistance, including inertia, grade resistance, and train friction during the accelerating period may easily be ten times that of the same train when running free on the level. Such a train cannot effectively utilize the torque of a prime mover whose average value is approximately uniform at all speeds. In order to meet conditions varying so widely between the driving force on the one hand and the resistance to be overcome on the other, a transmission is required which can deliver at the driven shaft the output of the engine either in the form of high torque at low speeds or low torque at high speeds, the engine shaft in the meantime running at its normal torque and speed.

A. Various Forms of Transmission

To meet this requirement a number of forms of transmission has been employed. Both hydraulic and pneumatic transmission has been used. In these forms of transmission a pump driven by the engine circulates some form of liquid or gas through appropriate motors on the driven axle. The pressure and volume of the circulating medium are varied by proper arrangement of valves or pump mechanism in order to vary the torque and speed of the driven motor. A description of the various devices has no place in the present paper. We can only say that in general all of these devices require the transmission of liquid or gas under high pressure through flexible pipes. In a locomotive or car such flexible high pressure piping presents a serious problem.

The most evident and simplest form of transmission is mechanical gearing between the engine shaft and the driving wheels. This has been widely used in automobiles and trucks where the problem of change in transmitted torque is solved by changing the gear ratio. When, however, it comes to applying such transmission to engines of the power, and to trains of the weight

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

required in railroad service, the disadvantages of the mechanical solution are more evident.

A simple mechanical connection between the engine and the driven shaft is unquestionably more efficient than any other form of transmission. If the service required only one speed at full output of the engine, no other form of transmission need be considered. The driving of a fan or a rotary pump may be instanced as illustrating the field in which mechanical connection between an internal combustion engine and its driven shaft might be suitable. In this case very little inertia is opposed at the driven shaft and the torque developed at that shaft rises to its full value with the speed. In transportation, on the other hand, where a high inertia is to be overcome, and the power of the prime mover is to be exerted over a wide range of tractive effort and speed, changes in gear ratio are required if mechanical connection is used between the driving and the driven shaft, and this introduces not only the complication and weight of gearing but other operating complications as well.

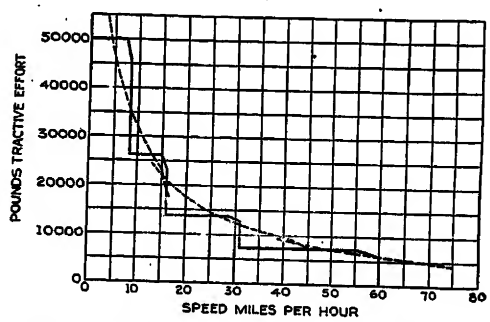

FIG. 1—SPEED-TRACTIVE EFFORT OF DIESEL LOCOMOTIVE

Full line—mechanical transmission
Broken line—electric transmission

Fig. 1 shows superposed the speed-tractive effort characteristics of two 1300-hp. oil engine locomotives. The full line is the characteristic of a locomotive with mechanical transmission. The dotted curve is that of an oil-electric locomotive. The difference in operating results is immediately evident. The mechanical transmission is furnished with four different gear ratios. For each of these the locomotive develops an approximately constant tractive effort with speeds varying up to the maximum speed set by the maximum rotative speed of the engine. The result of this is that the curve of the mechanical transmission appears as a series of steps corresponding to the different gear ratios. At each of these the speed of the train is directly proportional to the rotative speed of the engine, the engine shaft and driving wheels being tied together by direct gearing.

a. For each of these gear ratios there is only one point where the engine is developing its normal rated horsepower. Therefore, in the whole of the mechanical transmission characteristic there are only four points where the full normal engine horsepower is utilized. The question of utilization of the full engine horsepower through a wide range of service is one that does not apply to an engine using mechanical transmission.

b. In changing from one gear ratio to the next, it is necessary to throw out the clutch; in other words, to entirely disconnect the engine from the driving mechanism. At the instant of making the change from one gearing to the next, the tractive effort falls to zero. When such a transmission is applied to a locomotive pulling a long train, such a change in tractive effort is certain to cause surges in the train, and from such reports as have been published on the operation of mechanical drive locomotives, it is evident that it is only by careful manipulation that broken couplings are avoided in handling long trains. Apparently no mechanical drive locomotive has been developed up to the present time which avoids this difficulty of losing tractive effort at the instant of making change from one gear ratio to the next.

c. The engine shaft and driving wheel being tied together by a mechanical gearing, the speed of one is fixed and limited by the other as long as the engine is coupled to the transmission gears. The maximum train speed at any gear ratio is fixed by the engine speed. The train cannot run at speeds higher than those corresponding to the engine speed without throwing out the clutch and even when coasting within the allowable limits of engine speed, the engine friction under idling throttle will present considerable retardation to the train.

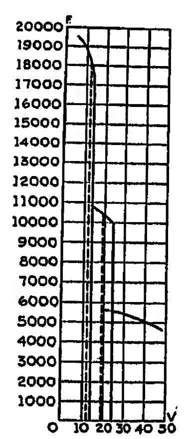

FIG. 2—SPEED-TRACTIVE EFFORT DIESEL LOCOMOTIVE WITH MECHANICAL TRANSMISSION

d. The rigidity of the connection between engine and driving wheels transmits road bed shocks and inequalities back to the engine. Engine builders complain of the effect of these shocks and the increased maintenance of engine resulting from them.

Fig. 2 shows the speed tractive effort curve of the Lomonossoff locomotive with mechanical gearing built for the Russian Railways and reported at the World Power Conference in 1928 (Report N-8, pp. 8 to 10). In this connection the report says: "Several breakages

of drawbar couplings occurred at the moment when the change of speed was effected. These breakages never happened later when trains were running on the line, but sometimes the couplings broke when the train was starting." This report appears to confirm the statements made in the preceding paragraphs.

B. Electric Transmission

No extensive description is required of the electric drive. With this transmission the internal combustion engine drives a generator, and the current generated is utilized in motors connected to the driving wheels. Certain features of this transmission will at once be appreciated by anyone familiar with application of electric power.

a. There is entire freedom of location of apparatus. The position of the engine, for example, is not dependent upon its relations to the driving axles as is the case where mechanical gearing connects the two.

b. The engine is not subjected to road shocks or inequality of road bed reflected back through the transmission.

c. The location of the operator is independent of the engine. By means of remote control the locomotive may be operated from any position that may be selected.

d. Since the power of the engine is developed in the form of current and voltage, the same power may be obtained with a wide variation of values of current and voltage and a correspondingly wide range of tractive effort and speed at the driving motors.

e. This variation of voltage may be gradual through gradually increasing values corresponding to the decreasing values of current, thus obtaining a gradual variation of tractive effort and speed at the driving motors without sudden breaks or fluctuations as illustrated in Figs. 1 and 2.

f. The engine speed is not a rigid function of the speed of the train, so that advantage may be taken of idling the engine or of shutting it down with the train coasting at full speed, or the engine may be driven at normal or even at reduced speed, if more efficient, with the train running at its maximum speed.

While these general features are self-evident to anyone familiar with electric operation, the following sections discuss some of the problems that have presented themselves and the methods which have been used to solve them.

C. Electric Transmission Problems

We have mentioned above the fact that with mechanical drive it is possible to utilize the engine horsepower only at a few limited points, while with electric drive it is possible to do so through a wide range of speed and tractive effort and with a gradual variation from one value to the next. A great deal of thought has been devoted by electrical engineers to the best method of obtaining this result.

a. Fitting Generator to Engine Curve. Fig. 3 presents three curves with amperes and volts as coordinates. Of these, Curve *a* is a rectangular hyperbola. The product of the two coordinates is constant. This represents, therefore, a constant output and may be called the "engine curve" as every point on it represents the same output. The ideal electric drive would require a generator with this characteristic which would develop a current at low voltages limited only by the slipping point of the wheels and a voltage at low currents limited only by the maximum safe locomotive or car speed. Such an ideal generator would fit the engine curve throughout. A practical generator, however, is limited in voltage by the commutating characteristics to a certain maximum voltage, and is limited by the carrying capacity of commutator and brushes to a certain maximum current. The characteristic of such a practical generator is shown in Curve *b* of Fig. 3. Points to the right hand side of the engine curve represent power in excess of the engine and are, therefore, impossible of attainment. For this reason it is necessary to devise some means of reducing the generator voltage for points

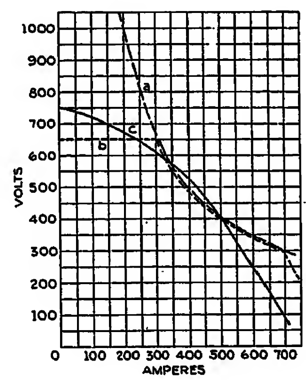

Fig. 3—Electric Transmission Characteristics

a— — — — Engine characteristics
b – – – – – Generator—manual regulation
c————Generator—inherent regulation

lying between certain limits. Using as an illustration the values given in Fig. 3, when the current reaches 300 amperes the engine is fully loaded and beyond this point, the voltage must be reduced at a rate proportional to the increase of current if the generator curve is to follow the engine curve.

b. Hand Control. The most obvious method of obtaining this result is by hand control of the generator field. Fig. 4 shows a method of connection which has been used on a number of the early gas-electric cars in which the operator controlled the strength of the generator field by hand. To take full advantage of this method, it was necessary for the operator to hold the voltage by hand regulation of the field current at a point that would just load the engine to its full capacity and still not overload it. As a matter of fact, the operators soon developed a practical sense to guide them in selecting the proper setting of field strength, and with a skillful and careful operator no more efficient form of control could be devised; but it is evident

that a careless operator could easily hold a field strength which would either overload the engine or underload it. In neither of these conditions would he obtain a power output equal to the full capacity of the equipment.

c. Automatic Differential Control. Another method of control which is very widely used and which automatically approximates very closely the desired results is differential control. The results which can be obtained by this control are shown in Curve *c* of Fig. 3. In this the inherent regulation of the generator gives

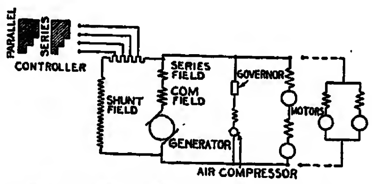

FIG. 4—CONNECTIONS FOR MANUAL CONTROL OF GENERATOR VOLTAGE (SEE CURVE B FIG. 3)

it a drooping characteristic so that it does not exceed a maximum given voltage at no-load nor a maximum current at full load, nor does it overrun the engine curve so as to overload the engine. A method of connection which has been used to obtain this result is shown in Fig. 5. In this the excitation of the main generator is obtained from a separate exciter mounted on the engine shaft. This separate excitation by itself would give an approximately constant voltage at all loads for a given engine speed. In addition the generator is wound with a differential series field giving it a drooping characteristic. By proper proportioning of the two fields the generator characteristic can be made to coincide with the engine curve at one point. If the generator curve slightly exceeds the engine curve, the result

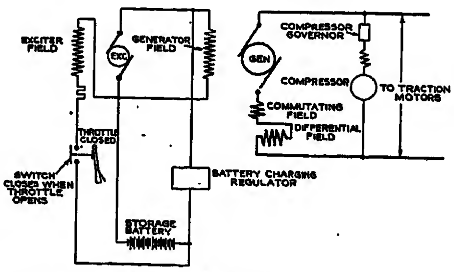

FIG. 5—CONNECTIONS FOR DIFFERENTIAL CONTROL OR INHERENT REGULATION OF GENERATOR VOLTAGE (SEE CURVE *c* FIG. 3)

will be that the engine will slow down, thus reducing the voltage coordinates of the characteristic and giving it a slightly concave shape at this point. In any event, the regulation of the engine governor has an important influence. If the generator curve just touches the engine curve and loads the engine at one point, the engine will carry less than its full load at points to one side and the other of the full load point with the result that in any case the generator characteristic will assume the shape shown in Fig. 6. Incidentally, the curve of Fig. 6 is the average of tests on five 200-kw. engine generator sets and can, therefore, be considered fairly representative of what may be found in a practical case. The exciter as shown in Fig. 5 derives its field initially from a storage battery. As the speed of the engine generator set increases, the voltage of the exciter rises, and when it reaches a value greater than that of the battery the automatic reverse current relay closes, the exciter begins charging the battery and becomes self-exciting.

Another modification of this connection is shown in

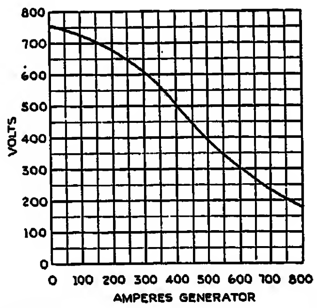

FIG. 6—VOLT—AMPERE CHARACTERISTIC OF COMBINED ENGINE GENERATOR SET

Fig. 7 where the differential series field is applied to the exciter, and reduces the voltage of the exciter which in turn reduces the excitation of the main generator. The advantage of this method of connection is that the space required for the same effect, if applied to the exciter, is less than that required if applied to the main generator, and it therefore reduces the size, weight, and cost of the whole generator exciter equipment. A large majority of the internal combustion electrically driven rail cars and locomotives which are in service in the United States are equipped with one or the other of the two methods of connection, shown in Fig. 6 or Fig. 7.

We have mentioned above the use of an "exciter" for furnishing the necessary excitation to the main generator. The term "auxiliary generator" would perhaps

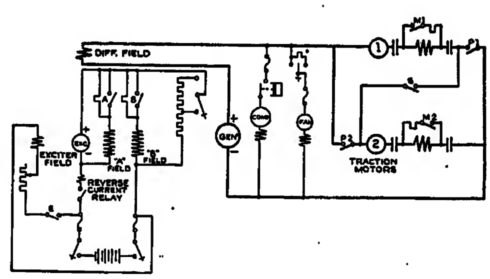

FIG. 7—CONNECTIONS FOR DIFFERENTIAL CONTROL WITH VOLTAGE REGULATION APPLIED TO EXCITER

be a more general and comprehensive term as this carries other circuits besides the generator excitation. It is a little difficult to draw a sharp distinction between the two terms. In this paper when the main function of the machine is to furnish excitation we have used the term "exciter," and when additional circuits are carried from it, we have mentioned it as an "auxiliary generator." Possibly a more consistent convention would be to call it an "exciter" if driven from the same shaft

as the main engine, and an "auxiliary generator", when driven from a separate auxiliary engine, but as a description of the problems and circuits involved does not depend on the method of driving, we have not attempted to draw the distinction along this line.

d. Battery Charging Field. Fig. 7 introduces a variation which has not been mentioned up to this point but which is widely used; that is, in the use of a generator field winding in two sections, one of which,

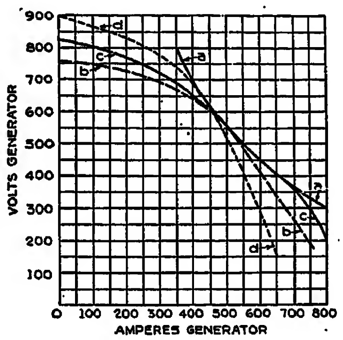

FIG. 8—VOLT-AMPERE CHARACTERISTIC.

a—Engine curve 400-hp. engine
b—Generator characteristic constant speed
c—Generator characteristic considering engine regulation
d—Generator characteristic with "dual control"

the *A* field, is excited directly and continuously from the exciter and the other, the *B* field, is in series with the battery and is only excited when the exciter voltage is high enough for battery charging. This arrangement of the field has several functions.

(1) It improves the efficiency of battery charging. Considering as we are, a variable speed engine there must be a certain range in speed during which the battery is charged. An equipment which would charge the battery only at its maximum speed would not furnish sufficient battery charging for ordinary purposes and if the battery is to be charged through a range of speed and voltage a cushioning resistance must be inserted between the charging generator and the battery. The use of the *B* field as this cushioning resistance makes use for excitation of the power which would otherwise be wasted in a rheostat.

(2) It produces better battery charging characteristics than would be produced by a mere cushioning resistance. Since the *B* field adds to the voltage of the main generator, it follows that a given maximum voltage of that generator will be obtained with a lower excitation voltage than if the battery charging current flowed through a dead resistance. The fluctuations of battery charging current are, therefore, less when delivered through a *B* field than through a dead resistance of the same value.

(3) The *B* field has a still more important function in its effect on the generator characteristic. For rapid acceleration of the train it is necessary that the full engine output should be obtained as rapidly as possible. At full engine speed the generator excitation and torque should be such that the generator loads the engine to its full capacity. At the same time at speeds below full speed there should be a margin between the possible torque of the engine and that required by the generator in order to allow the engine to come rapidly up to speed. The use of the *B* field has the characteristic that the maximum excitation of the generator, *i. e.*, the sum of the *A* and *B* field, is not reached until the engine has come up to a speed sufficiently high to permit the exciter to charge the battery, at which time the *B* field adds its quota to the excitation of the generator and brings up the torque of the generator to balance the engine torque at full speed, load, and output.

e. Single Motor vs. Multiple Motor Load. One feature that is not always recognized is that different characteristics of the generator are advisable for a single motor load as compared with a multiple motor load. For a multiple motor equipment a wide range of correspondence between the engine and generator characteristics is not necessary as modifications in the connection of the motors can keep the generator working at or near the point where it fully loads the engine. Fig. 8 shows the engine and generator characteristics of a 400-hp. engine (Curve *a*) and generator (Curve *b*) at a normal speed of 900 rev. per min. Curve *c* shows the effect of engine speed variation on the shape of the generator curve. The Curves *a* and *c* practically coincide through the range from 600 volts, 450 amperes down to 350 volts, 700 amperes. An equipment of two GE-297 motors would be conveniently used with such an engine generator set. Fig. 9 shows the speed-

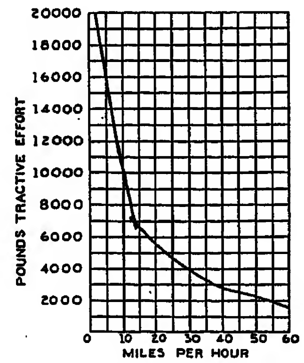

FIG. 9—SPEED-TRACTIVE EFFORT CURVE

Equipment:
1—400-hp. engine
1—Generator, differential control
2—GE-297 motors

tractive effort characteristics of such an equipment. The maximum tractive effort of 20,000 lb. is exerted at 700 amperes per motor in the series position. The change in the controller from series to parallel occurs at 15 mi. per hr., which corresponds to a current of 330 amperes. The generator load (referring to Fig. 8) is therefore changed at this point from 330 amperes and 700 volts to 660 amperes and 400 volts. The change from parallel connection to shunted field connection

occurs at 200 amperes and changes the generator load from 400 amperes and 650 volts to 480 amperes and 550 volts. The effect of this is that through most of the range of the control the generator and engine are running at very nearly their full load. Fig. 10 shows more evidently how nearly the full horsepower of the engine is used throughout the range.

f. Full Utilization of Engine Power. Where, on the other hand, only one motor is driven from one en-

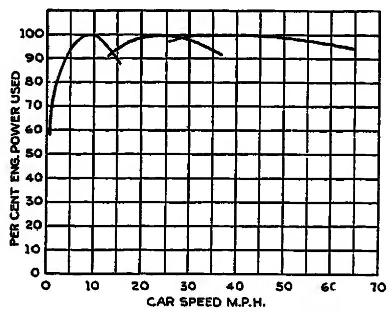

Fig. 10—Available Power

Equipment:
1—400-hp. engine
1—Generator, differential control
2—GE-297 motors

gine generator set a wider range of contact is advisable between engine and generator curve; since a variation in the tractive effort can no longer be obtained by varying the combinations of motor circuits, but can only be obtained by variations in the current delivered by the generator. Also, where on account of limited engine power or exacting service conditions, it is desired to use the engine equipment more nearly to its full capacity than shown on Fig. 10, the complications and cost of an equipment for that purpose may have to be considered.

A simple method of thus obtaining a wider use of the engine power is by use of "dual control." Fig. 11 shows

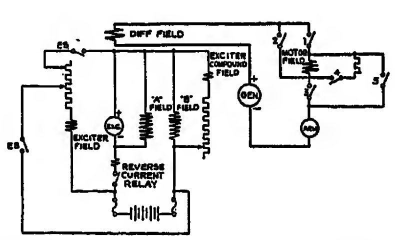

Fig. 11—Connections for Dual Control. See Curve *c* Fig. 8

shows the same connections already discussed, but with the addition of a switch *E S* which alters the resistance in series with the exciter field. When switch *E S* is closed and *E B* is open, the exciter becomes self-exciting; its characteristic and therefore that of the main generator becomes steeper and more sensitive to variations in engine speed or differential field current. The characteristic will therefore take a higher and steeper form as shown in Curve *D* of Fig. 8. This switch *E S* may either be a manually operated switch as a part of the controller, or may be a contactor operated by a relay at a predetermined current value. If such an arrangement were used in the case which has been used as an illustration in Figs. 9 and 10, a convenient value for operating this relay would be approximately 450 amperes. With this addition the characteristics of the generator would lie along the line *d* from no load to 450 amperes and along the line *b* for current values above that point.

Where a still wider utilization of the engine power is desired, some automatic means of progressively varying the generator field must be employed. Referring again to Fig. 4, which shows the simplest form of connection, the excitation of the generator must be controlled by some automatic means in order to keep the engine fully loaded at all times, thus automatically reproducing the action of a competent and careful engineer. The relay or other device used for this purpose can be arranged to vary the field current to maintain a constant value of any one of several functions. For example, such a device might be operated in connection with a wattmeter or a speed indicator to maintain in one case a constant value of kilowatt output, or, in the other case, a constant speed; or with some other device, to maintain a constant value of some other function. As a matter of practise, the generator is made

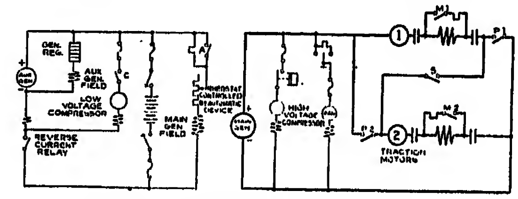

Fig. 12—Automatic Control

separately excited rather than self-excited as shown in Fig. 4. This maintains the field strength for each setting of the rheostat more accurately and definitely than could be obtained by self-excitation. Fig. 12 shows the connections for such a control in which the excitation of the main generator is taken from the auxiliary generator through a rheostat whose resistance is automatically controlled.

One application of such a device as has been described above is an arrangement in which the resistance in series with the generator field is controlled by a relay of which one element corresponds to the current in the generator field and the other to the current in the generator armature. The neutral position of this relay corresponds to some product of the field current and armature current in the main generator. Any variation in load on the generator causes the relay to move so as to adjust the generator field to a value such that the product of the field current and armature current is brought back to the original predetermined value or torque. This evidently demands a certain torque out of the engine independent of the engine condition. For other than full engine speed the torque relay must be adjusted to correspond to the torque of the engine at those speeds.

Another plan for wide utilization of the engine power is based on maintaining a constant engine speed. In this the resistance in series with the generator field is controlled by a relay which in turn is controlled by the engine governor. This relay, therefore, adjusts the strength of the generator field and voltage to such a value that it will hold a given speed of the engine for any value of the armature current. Independently

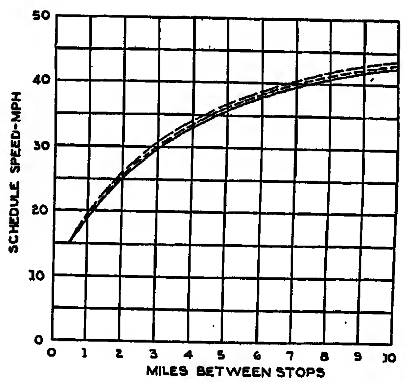

Fig. 13—Schedule Speed 115-Ton Train

400-Hp. gas-electric equipment
——— Differential generator constant speed
– – – Differential generator with engine regulation
— — Automatic control maximum utilization of engine power

of the engine condition this control, therefore, will always bring the engine back to the normal speed and if the engine, for example, will not deliver its full horsepower the generator output will be cut town to correspond. For other than full engine speed the relay must be changed to correspond to the new engine speed simultaneously with the new setting of the engine speed governor.

Whether any plan for full utilization is to be recommended depends upon economic considerations. It is obvious that with the best utilization the voltage is limited on the one hand and the armature current on the other by generator design. The curves of Fig. 13 have been worked up to show the schedules which are obtainable with a 115-ton train and a 400-hp. engine generator set. The lower curve indicates the schedule obtainable with differential control, the engine running at a constant speed, and the upper curve shows the schedule obtainable with full utilization of the engine power through the maximum ranges of voltage and current. As has been mentioned previously, even with differential control the engine regulation or the use of the B field will cause a certain amount of shifting of the differential characteristic up toward the full utilization curve and the actual result will be that the differential control will give schedules indicated by the dotted line running about midway between the theoretical differential control and the theoretical full utilization control. Whether the addition of the devices necessary to obtain any form of automatic field control as compared with those required for the simple inherent characteristics of the so-called differential control is or is not justified, can only be decided by economic considerations such as price, cost of maintenance, and the results of practical operation.

g. Auxiliaries at Idling. Nothing has been said as to the operation of auxiliary circuits such as compressors, ventilating fans, etc. Most of the illustrations up to this point have shown these circuits as connected to the main generator circuit. This naturally involves variable voltage on the auxiliary circuits with variable speeds and output. A large number of equipments, both on cars and locomotives, have been installed with this arrangement and are in satisfactory practical operation. When it comes to a question of traffic more exacting or complicated in its demands it may be found that some more elaborate arrangement is necessary. This requirement would naturally be presented first on locomotives used for switching service. Here the engine is idling during a large fraction of the time that the locomotive is in service. During the time involved in waiting at switches and making up trains although the engine may be idling, full air pressure is required for brakes and the battery must be kept charged. For motor car service this requirement is not so insistent as the engine is running at full speed during the greater proportion of the time that the car is in service; but even here certain schedules may demonstrate the advantages of compressor operation and battery charging at idling speeds. Where a long grade offers the possibility of coasting without power, it should be possible to take advantage of the characteristics of electrical operation and allow the engine to run at idling speed; and occasionally other classes of service are encountered where long periods of operation at reduced power offer an advantage in air compressor operation or battery charging at idling speed of the engine. Several plans have been evolved to meet this condition.

Fig. 14 shows an arrangement of equipment which has

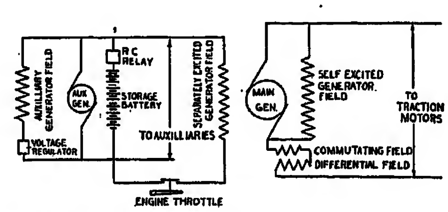

Fig. 14—Differential Control with Constant Voltage on Auxiliaries

been widely used on locomotives. In this scheme of connection the auxiliary generator is equipped with a voltage regulator which holds its voltage constant through the operating range of the engine speed. The storage battery, generator field, and all auxiliaries are wound for the voltage carried on the auxiliary generator. It will be noted that there is now no necessity for a charging resistance in series with the battery and the possibility of using the B field which has been previously described is eliminated. In order to com-

pensate for this the generator is given a certain amount of self exciting field which has the same effect as the *B* field in that it brings up the voltage and torque of the generator as it comes up to full speed and loads the engine at this point, although leaving a reduced voltage and reduced torque at lower speeds.

The plan last described is one that is particularly applicable to equipments in which an oil engine is the prime mover. The idling speed of an oil engine is approximately 50 per cent of its normal speed and it is

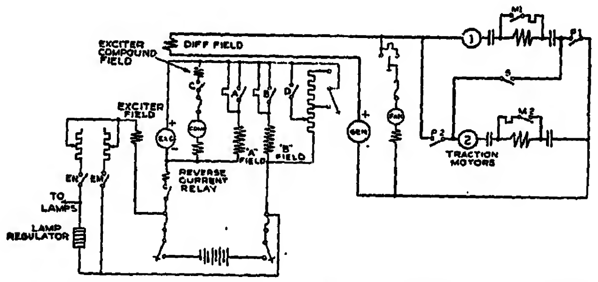

Fig. 15—Variable Voltage on Auxiliaries, But Operation at Idling Speeds

perfectly feasible to design an auxiliary generator of sufficient capacity to hold its full voltage down to half speed. A gasoline engine, however, frequently has an idling speed of 20 per cent of its full speed and an auxiliary generator with capacity for holding full voltage down to 20 per cent of its full speed would involve a serious increase in weight and dimensions. Fig. 15 shows a scheme of connections which has been applied to motor car equipments. It avoids the excessive size of auxiliary generator and partially meets the requirement of furnishing air and battery charging. In this case the compressor is carried on the auxiliary generator. At normal speeds this auxiliary generator is excited through a switch *E N* to normal voltage. At idling speeds the motor circuits are opened, the generator field circuits are cut to a minimum by the opening of the field switches *A* and *B*, the auxiliary generator is over-excited by closing the switch *E N*, and the auxiliary generator develops sufficient voltage to charge the battery through the small resistance introduced by closing the switch *D*. The compound field of the auxiliary generator is connected in series with the compressor so that when the compressor starts it still further builds up or at least maintains this voltage. As a general thing, in order to keep the size of the auxiliary generator as small as possible, no attempt is made to maintain full voltage on this generator at idling and the compressor does not develop its full rating under these conditions.

A number of other combinations has been suggested. One is operating the auxiliaries from the low voltage auxiliary generator during full speed and shifting the connections to the main generator in order to take advantage of whatever voltage it may develop during idling. Other combinations of circuits have been proposed with the general intention of utilizing what voltage is available at reduced speeds. None of these combinations being of wide practical application, we have not discussed or illustrated the details of the connections. Still other combinations of circuits to obtain similar results will suggest themselves to others interested in the subject.

The plans discussed above readily indicate that the ideal arrangement for handling auxiliaries would be one in which they are entirely independent of the main generator. In other words, by the installation of a separate engine for handling the auxiliaries at constant speed and constant voltage. If, in combination with this, automatic control of the speed of the main engine is installed, we would have an arrangement that would be applicable in all cases, either to locomotive or car equipments where the capacity and cost of the equipment or the exacting demands of the service make it economically advisable. Fig. 12 illustrates this arrangement, if we assume that the auxiliary generator is operated by a separate engine at constant speed and furnishes power for a compressor, the main generator field and battery charging. In order to reduce the size of auxiliary equipment, a high-voltage compressor is carried on the main generator and when the engine is at full speed, full air capacity is obtained from the two compressors in parallel.

h. Combination Generator-Battery Power Plant. A form of electric transmission which presents some striking advantages and which seems to have a wide application is the use of a storage battery in parallel with the main generator. Fig. 16 shows a diagram of connections for such an equipment and it will be noted that the arrangement of the equipment is radically altered by the introduction of the battery.

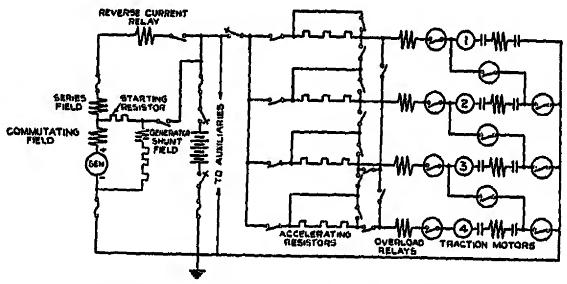

Fig. 16—Connections for Combination Generator-Battery Power Plant

No exciter is required as the excitation and all auxiliary operation is taken from the battery.

The generator operates at a constant speed and approximately constant voltage as required for battery charging.

The battery carries all the peak loads, leaving the generator and engine to carry a fairly uniform load. The generator load is added to the battery output in periods of high demand and is expended in charging the battery when the load falls off. This uniform load

and high load factor is apparent in its effect on the fuel efficiency and engine maintenance.

Since the battery maintains an approximately constant voltage, the control is of the constant potential type similar to that on equipments using trolley or other constant potential source of power. In general, the equipment and its control is so similar to trolley control and operation that it would not be mentioned in this paper except that it illustrates one of the combinations which are used in transforming the power of an internal combustion engine into power for traction purposes.

D. Engine Characteristics as Affecting Electric Equipment

Up to this point the discussion has confined itself to control of the power transmitted at full output of the engine. It is necessary to operate and control such an equipment also at reduced output either during acceleration or during operation of trains at reduced speeds. The features of the electric control for such reduced power are conditioned largely on the engine characteristics and control. It is necessary to distinguish therefore between engines for constant speed and engines for variable speed, and between engines of different capacity.

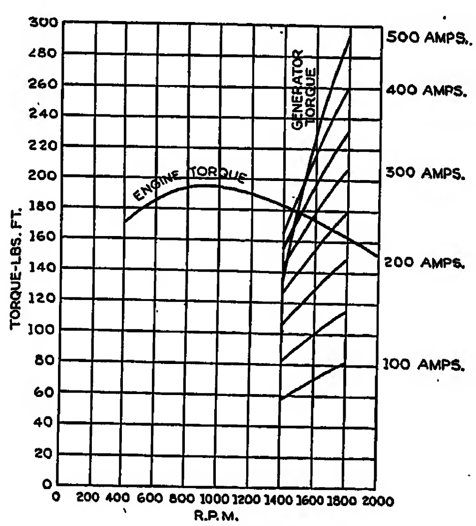

Fig. 17—Speed-Torque Characteristics 55-hp. Engine and Self-Excited Generator

With an engine designed for constant speed, the control of the train speed is necessarily by control of the generator voltage. This type of engine running at a constant speed with voltage control has not been widely used in this country although it is used in Europe.

The equipment used in this country generally obtains reduced output and control of the train speed by varying the engine speed. While this is true in a general sense the problem presented varies with the type of engine. It is frequently stated as a fact that the torque of an internal combustion engine is approximately constant. Whether the electric equipment is to be adjusted to take advantage of this torque depends on the design of the engine.

a. Small Engines. For small engines, such as are used on busses, for example, the full torque of the engine is generally available at all engine speeds. The bus generator is therefore designed to deliver a torque equal to the full torque of the engine within normal operating limits which may be 75 per cent to 100 per cent of full speed. Fig. 17 shows the torque curve of a typical bus engine and the torque curves of the corresponding generator with normal excitation at various speeds. It will be seen that the full torque on the generator at full speed may far exceed that of the engine. The generator can therefore absorb the full

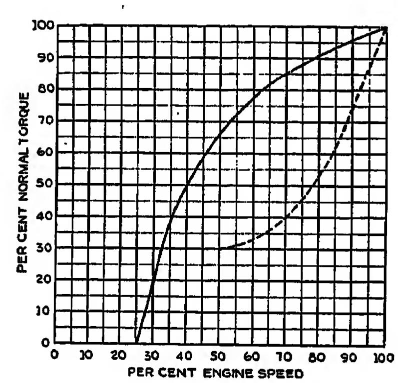

Fig. 18—Variation in Engine Torque Characteristics

torque of the engine at full speed. By over-excitation of the generator this torque can be raised so as to cut the torque at still lower speeds and this is a method very generally used on such equipments.

As a general thing the following represents the sequence of acceleration and operation of such an equipment.

The bus is accelerated at full engine speed and full load which is obtained by a partially excited field. After the full running speed has been obtained, the generator is excited to its full excitation, the increased torque on the generator pulls down the engine speed, and a balance is obtained with the engine at perhaps 75 per cent of its full speed driving the generator at full voltage with full field. When more power than this is desired the generator field is weakened, allowing the engine to come up to full speed and full horsepower. Stated in other words it may be said that with an engine of this sort it is possible to operate the torque of the generator balanced directly against the maximum torque of the engine at that speed. This scheme of operation can only be used with an engine of such design that the generator torque can be allowed to absorb all the torque of the engine.

One comment should be made on the curves of Fig. 17. The torque curve of the engine there shown, although typical of engines as they are designed today, is not

what is most desirable for electric transmission. The peak value of this torque curve occurs at less than 50 per cent of full speed. A more satisfactory engine would be one that carried its maximum torque at a higher fraction of full speed; in fact, for electric transmission it would be preferable to have a constant torque of the engine within the range of operation, and one which did not fall off with increasing speeds.

b. Large Engines. With engines as they are designed today we find that when we reach a certain capacity the engine designers raise objection from the standpoint of excessive pressure on engine bearings, excessive temperatures of exhaust gases, danger of

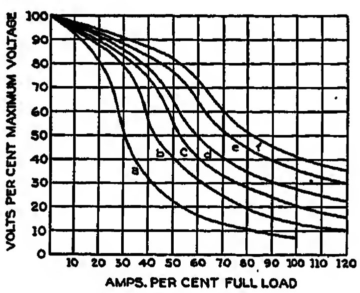

FIG. 19—GENERATOR CHARACTERISTICS. THROTTLE CONTROL OF ENGINE

Curves a, b, c etc. represent various throttle openings

pre-ignition and other features to an electric equipment which will absorb the full torque possible from the engine at reduced speeds. If such a requirement is to be met the field and torque of the generator must be modified to correspond to the desirable engine torque. This will generally be done by operating a section of the generator field rheostat in connection with the engine control handle so as to change the generator field simultaneously with the engine speed. What that reduction amounts to and the characteristics of the equipment at various speeds depends entirely on the engine design. As an illustration the curves of Fig. 18 show various conditions of torque which have been encountered in practise as affecting the design of electric equipment.

c. Engine Control. In connection with the combination of engine and generator the generator characteristics are affected by the question of whether the engine speed is controlled by the throttle or by adjustment of the governor. In the one case the fuel supply is limited to hold down the maximum horsepower output but at light loads the engine runs up to its full speed. In the other case, the speed is maintained at any step of the control independently of the load. The consequent difference in the shapes of the generator characteristics on various steps is best seen in the curves of Figs. 19 and 20. Both of the equipments in question are of approximately the same power and designed for approximately the same service and graduation of control steps. Fig. 19 illustrates the characteristics produced by throttle control of the engine and Fig. 20 those produced by governor control of the engine.

E. CONCLUSION

We have said nothing in regard to multiple power plants consisting of more than one engine generator set. The variations in connections which would be introduced by such a multiplication of power plants would seem to be self-evident. For any of the typical schemes of connection which have been discussed, the addition of another engine generator set would simply mean the addition of the necessary cross connections to operate the two plants in parallel, unless as is sometimes the case the several plants are operated independently of each other, each engine generator set furnishing power to its own motors. The additional illustrations covering such combinations have been omitted as they would unnecessarily complicate the discussion.

It may seem to one unfamiliar with this topic that the various questions raised in this paper and the various solutions indicated are illustrative of the complexity of electrical transmission and control. On the contrary we have shown some of the problems which present themselves for solution, and the questions which we have discussed are only another illustration of the adaptability of electric drive to meet varying conditions.

The discussion of the various problems presented in the transmission and control of electric power for internal combustion engines for transportation is not assumed to be exhaustive. We have attempted to describe some of the principal problems presenting themselves to an operating and designing engineer working on the subject, as well as some of the solutions of these problems. Other problems will present themselves under new conditions and other connections and other solutions will suggest themselves to other engineers. We believe, however, that we have given a very fair summary of the situation as it is presented in American railway practise.

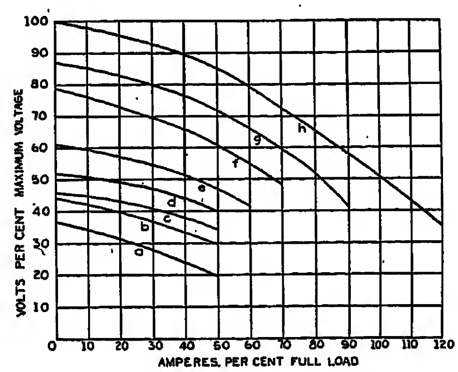

FIG. 20—GENERATOR CHARACTERISTICS. GOVERNOR CONTROL OF ENGINE

Curves a, b, c, etc. represent various governor settings and engine speeds

Discussion

H. Rosenthal: In comparing the characteristic of an oil-electric locomotive with a mechanical transmission having four different gear ratios, Mr. Dodd says—

> "For each of these gear ratios there is only one point where the engine is developing its normal rated horsepower. Therefore, in the whole of the mechanical transmission characteristics there are only four points where the full normal horsepower is utilized."

While this statement is essentially correct, it does not indicate the infrequency in operation with which the full engine horsepower could be utilized.

With the four different gear ratio transmission, there are four car speeds (each corresponding to the same engine speed) where the engine could develop maximum horsepower. With the car operating at any one of these speeds, the amount of power utilized by the car will depend not on the amount of power which the engine can deliver at that speed but on the tractive resistance of the vehicle, and for any particular car and condition of the road bed at that speed there will be only one grade at which the full engine horsepower can be utilized.

Thus at only four car speeds can the engine develop the maximum horsepower, and on only a single grade at each of these four speeds can the vehicle absorb this maximum power.

T. H. Murphy: Mr. Dodd's paper is of considerable interest to electrical engineers who are concerned with the design and application of equipment for railroad automotive rolling stock. In conclusion, he points out the fact that electrical transmission is very flexible and may be adapted to meet any of the conditions required without excessive complication.

Engineers disagree only as to the extent to which the electrical equipment shall perform the desired functions. In the development stages, when engines were the real unknown factors, the simplest electrical transmissions were used with little thought to the best automatic loading and operation of auxiliaries. Hand and automatic differential control were used in various forms on the early cars. Now that engines have proven reliable in service, more importance is attached to the transmission and much thought has been given to eliminate or improve the undesirable loading features of the early schemes and to furnish satisfactory operation of the necessary auxiliary equipment.

The essentials of a modern control are:

1. Economical transmission of power.
2. Automatic full-speed compressor operation at all times.
3. Ample supply of power for battery charging.
4. Full loading of the engine over a wide range of vehicle speed.

Attempts are made to combine all of these features in the present day transmission systems.

Mr. Dodd's paper gives in detail the developments with differential equipment to obtain the essentials of a modern control but I do not believe that he stresses sufficiently other control systems. The no load voltage of Curve B is only 650 and that for Curve C 750. The comparison may be for different size machines. Further C crosses the engine curve and obviously produces an overload. The more efficient use of the engine by manual regulation would be indicated if Curve C were drawn to just touch the engine curve, as was done for Fig. 6, and the same no load voltage for the two machines used.

In describing the combined action of the engine and electrical equipment, Mr. Dodd states that concavity is produced by slowing down the engine. This is not shown by any curves. An opposite effect is shown, and that is a speeding up of the engine. If this is permissible with differential control, then higher loading speeds should be permitted with other forms of control. The result will be an increase in the performance difference between differential control and ideal loading.

Curves in Figs. 3, 6, and 8, indicate fixed characteristics built into the electrical equipment. Advance thought in electrical control has discarded the idea of constant characteristics, as it is well known that available engine power changes rapidly with engine temperature, atmospheric conditions, altitude and engine conditions. The system of control to be adopted should, therefore, provide automatic, flexible loading of the engine. When constant characteristics are built into the equipment, the maximum loading must be fixed below the normal minimum engine capabilities in order to prevent continuous overloading and low engine speed.

As pointed out by Mr. Dodd, a torque control has been developed that maintains a constant engine speed. This control is mechanically operated by the engine governor in one case and in the other by a voltage regulator that maintains constant engine speed. In either case the engine is uniformly loaded under all conditions.

With these schemes, devices are necessary in the generator field for regulation, but these are offset by the better loading obtained and the use of smaller generators. It can be seen from Fig. 8 that ideal loading could be obtained with a smaller generator than the one for which the curve is drawn.

Operation of auxiliary equipment is a very important item on gas-electric equipments. The use of the scheme shown by Fig. 14, requires a large auxiliary generator and a large main generator, thereby increasing the cost, weight and space of the electrical equipment. It has been found that it is a relatively simple and easy matter to operate the compressor and charge the battery from the main generator at idling speeds. No special apparatus is necessary in the auxiliary generator field to compensate for wide speed variation. From a theoretical standpoint, a separate engine undoubtedly presents desirable possibilities for operating auxiliaries, but from a practical standpoint, it has yet to be proven whether the additional maintenance required for this small engine will permit of its use.

Mr. Dodd has brought out the fact that the B field functions in connection with the battery charging and engine loading. It should be pointed out that the value of battery charging current is a function of the state of battery charge, and that, therefore, the strength of the B field must be a function of the battery condition. This means that engine loading must be somewhat dependent on battery condition. But this does not appear logical or justifiable. Furthermore, in studying the indicated differential control systems, it should be remembered that the auxiliary generator voltage varies almost as widely as the generator voltage. This means an unsatisfactory source of battery charging power, and the battery is apt to suffer. Charging regulators and lamps have been used in order to hold the battery charging current to a somewhat constant value. These devices have been merely a means of saving the battery from an inadequate charging source, and at best, the charging current must vary widely, be difficult of adjustment, besides being apparently difficult to maintain a fully charged battery without serious overcharge.

Auxiliaries for High-Voltage D-C. Multiple Unit Cars

BY C. J. AXTELL[1]
Associate, A. I. E. E.

Synopsis.—The selection and application of auxiliary electrical devices on a high-voltage multiple unit car is of almost as much importance as the application of the main traction apparatus and requires careful consideration.

This paper contains a description of the engineering features as worked out for electrified suburban lines operating on 1500-volt and 3000-volt systems.

The control circuits have become very generally standardized at 32-volts, which is also well adapted for interior illumination and headlights. A motor driven generator supplies 3- to 5-kw. power per unit for control lights and battery charging. Such devices as heaters and motor-generator sets, requiring a considerable amount of electrical power, are necessarily constructed to operate at trolley potential. On the 1500-volt system, the compressor can be operated directly from the line potential while on the 3000-volt systems, a double commutator motor driving the generator supplies a 1500-volt source of power for the compressor.

* * * * *

On any electric car used in a service where multiple unit operation is required, there is a number of electric devices other than those required to actually control the propulsion of the car. Among the more important are the air compressors, heaters, lights, headlights, electric control of air brakes, automatic couplers, whistles or horns, signals, etc. Some of these devices require several kilowatts of power; others but a few watts.

For the control of reasonably large amounts of power, equipment can be economically made to handle power from either 1500-volt or 3000-volt sources. There are, however, many of the smaller devices where such a high potential would necessitate the use of insulating materials entirely out of proportion to the size and importance of the device. Consequently the use of a low-voltage current supply has been very generally adopted for these secondary circuits. Another reason, by no means an unimportant one, is the necessity for having a low-voltage source of power for the headlights, where high-speed operation in suburban zones is required. One of the requirements of a good headlight is that the filament be concentrated as nearly as possible to the focus of a parabolic mirror. This requires a short, thick filament operating at a low voltage. Since it projects an intense light down the track and also produces sufficient diffusion at the side to illuminate the right of way, a 32-volt lamp gives almost ideal headlighting. Fortunately the 32-volt source of power is also ideal for the control and auxiliary circuits. Furthermore, since cars for this class of service must have an auxiliary battery for lighting in case of the failure of power from the distributing system, a 32-volt secondary potential can be most advantageously used.

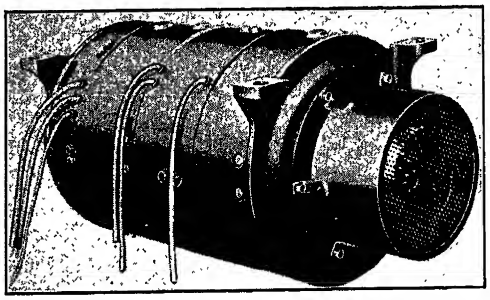

FIG. 1—3000-VOLT DYNAMOTOR GENERATOR

The only auxiliary device taking any appreciable amount of power, (except the heaters, which can be operated directly from the trolley source of potential), is the air compressor. On any system up to and including that with a 1500-volt trolley, the compressor will operate directly from the line potential. At the higher potentials, such as 3000 volts, the use of a dynamotor generator set fulfills the requirements. The dynamotor of this set has a dual function; the first, to furnish a source of power of one-half the line voltage for the operation of the air compressor, the second, to drive a small generator to supply current for the control, lights, headlight and other auxiliary circuits and also to maintain the auxiliary battery in a charged state. Since the dynamotor speed will vary with the line potential, it is necessary to provide a voltage regulator for the generator. The generator potential to be held will be governed by the lamps used and the number of cells and type of battery. With such a set, the battery can be floated continuously across the generator and kept in a fully charged condition.

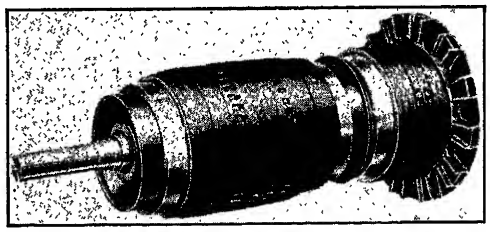

FIG. 2—ARMATURE OF 3000-VOLT DYNAMIC GENERATOR

1. Transportation Engg. Dept., General Electric Company, Erie, Pa.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930. Printed complete herein.

A description of the auxiliaries of two of the modern electrified steam railroad systems using high-voltage direct current, and operating multiple unit cars, may be of interest.

The Illinois Central Railroad suburban electrification in Chicago has a system potential of 1500 volts. This service is operated with 150 units, each consisting of a motor car and a trail car semi-permanently coupled. The length of the two-car unit is 145 ft. 5 in.; the weight, approximately 114 ton.

The Delaware, Lackawanna and Western Railroad suburban line, at Hoboken, N. J., is being electrified for operation at 3000 volts. There will be 141 units, each consisting of a motor car and trailer. The size of the cars is practically the same as those used by the Illinois Central Railroad.

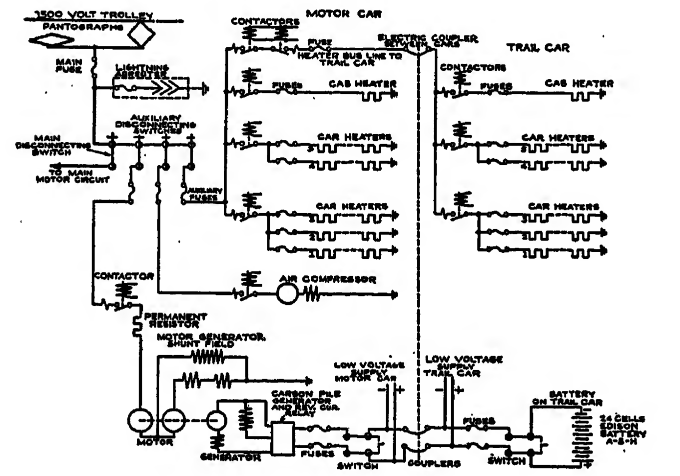

Fig. 3—Typical Connection Diagram of High-Voltage Circuits for 1500-Volt Multiple Unit Cars

The auxiliary devices and the source of power for supplying them are as follows:

Apparatus	Source of power
Electric heaters	Directly from trolley
Motor-generator (1500 volts)	" " "
Dynamotor generator (3000 volts)	" " "
Air compressor (1500-volt system)	" " "
(3000-volt system)	From mid-point of dynamotor
Lights, headlights, control current for motor controller, pantograph, heaters, compressor, doors, whistle or horn, signal, etc.	From generator or battery

Heaters

Electric heaters are now manufactured for operating directly from 1500-volt or 3000-volt sources of power and are arranged for underseat mounting. The heaters are of the same general outward appearance as have long been used on 600-volt systems. The heater element, however, is of greatly improved type. It is constructed as a helical coil imbedded in highly refractory insulating material in a steel tube. Thus the actual resistance wire is the completely protected. The regulations of the National Board of Fire Underwriters require that the temperature of the heater casing be limited to a relatively low value, which results in the operation of the heater elements at a much lower rating than is used in other classes of service. A high factor of safety exists therefore between the unit rating as applied to the heater and the actual point at which the heater element would fail.

On the multiple unit suburban cars of the Delaware, Lackawanna and Western electrification, the heaters operating from the 3000-volt trolley are placed under the seats. The main heaters consist of two 14-kw. circuits per car. Each circuit has forty 75-volt 350-watt elements in series. The heaters are distributed so that one unit in each circuit is mounted in a heater casing under each seat. On these 3000-volt heaters, there are two insulations in series between the resistor wire and the sheet steel casing. The wire imbedded in its steel sheath is tested at a potential of 3500 volts a-c. for one minute. The sheath of the unit is insulated from the steel casing with porcelain insulators. The complete heater receives a high-potential test of 10,000 volts, alternating current, for one minute from resistance element to casing.

The heater units are so mounted in the steel casing that all terminals and live parts are completely protected and the ventilating louvers arranged to prevent any possibility of inserting an umbrella rod, wire, or any conductor into the case, so that it could make a contact with the heater sheath or any live part. The heater casings are individually grounded to a No. 6 A. w. g. ground cable, running the length of the car on each side and connected at both ends to the car underframe. These individual heater circuits are protected by 8-ampere fuses of the expulsion type.

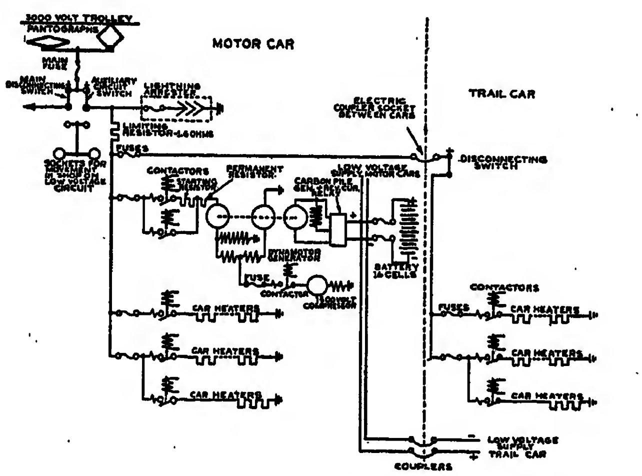

Fig. 4—Typical Connection Diagram of High-Voltage Circuits for 3000-Volt Multiple Unit Cars

The heat in the car is thermostatically controlled to maintain a constant temperature; 3000-volt magnetically operated contactors open and close the circuits for the heaters. These contactors are mounted in a

box underneath the car together with contactors for other auxiliary circuits. This type of contactor is used to permit switching on the heat, to warm up the cars previous to putting them in service, without having to maintain air pressure for operating electropneumatic contactors.

In each operating vestibule are three heaters of two, three, and five elements each. These heater

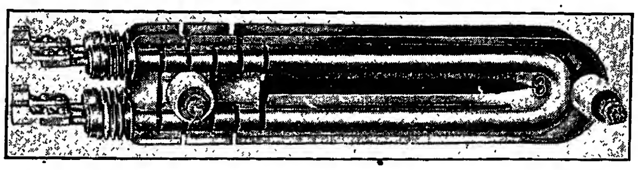

FIG. 5—3000-VOLT CAR HEATER UNITS

elements are rated 340 watts each, thus providing a total heater capacity of 3400 watts for the vestibule. The cab heater is controlled independent of the car heaters. A push-button switch is provided in the cab to switch the heaters on and off. This switch is also arranged so that it will be opened and shut off power to the heaters if the compartment door is closed, as is the case on all but the operating cab. Trail car heater equipment is a duplicate of the motor car, power being taken to the trail car through a 3000-volt auxiliary bus line located on the roof of the car.

During the development of these electric heaters, tests were made to determine what disturbance, if any, would occur if some heater element or cable near the trolley side of the circuit should become grounded. On a test in which a ground connection was deliberately made to leave only one element in the circuit, the protecting fuse blew, and it was found that the heater element had also open-circuited, but was not grounded

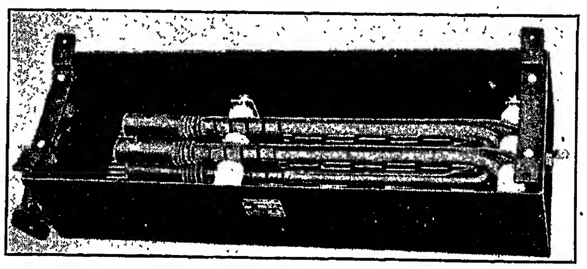

FIG. 6—3000-VOLT CAR HEATER

to its enclosing sheath. No noise or flash was perceptible in the heater case. Tests were also made with a greater number of heater elements in the circuit, under which condition, the fuse protected the circuit completely and the heater elements were not damaged. If the heater element fails, it simply opens up the circuit as does a fuse, but without grounding to the sheath or causing any disturbance. To determine whether or not, after this abuse, the resistor unit was open-circuited, it was necessary to test the unit. The above 3000-volt heaters were manufactured after the same general design as those which had been in service on the 1500-volt electrification of the Illinois Central Railroad, the principal differences being in the increased insulation used on the higher voltage heaters.

The control of the 1500-volt and the 3000-volt heaters is practically the same; the 1500-volt current supply for the heater on the trail car on the Illinois Central Railroad cars is carried through a special 1500-volt contact in the automatic electric car coupler. Provision is made, if the cars should pull apart, to open

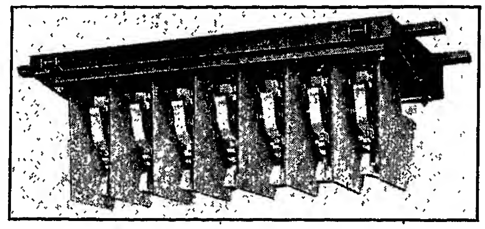

FIG. 7—1500-VOLT AUXILIARY CONTACTOR GROUP

the control circuit of the two heater bus-line contactors. A control switch is also provided on the lever interlocking the coupler to open the control circuit of these contactors previous to the electric couplers being parted.

MOTOR-GENERATOR AND DYNAMOTOR GENERATOR SETS

To supply the various devices with low-voltage source of power, a motor operating from the line potential driving a generator of sufficient capacity for the low-voltage auxiliary circuits is used. On the 1500-volt

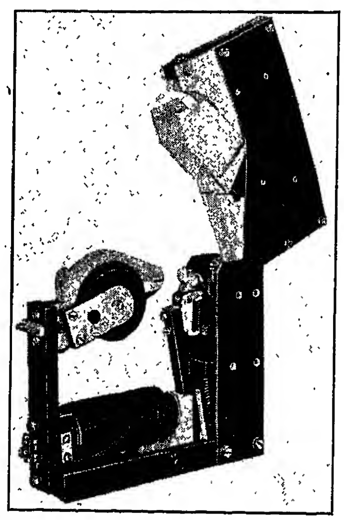

FIG. 8—3000-VOLT AUXILIARY CONTACTOR

electrification of the Illinois Central, a motor-generator set of 3.5-kw. capacity was used. The set consists of a motor and a generator in a single frame. The motor is a compound-wound machine with sufficient series field to give good starting characteristics when connected directly to the line, and to produce a stable machine operating on a trolley of fluctuating potential. A permanent resistance of approximately six ohms is

used to cut down the first rush of current when starting, and permit the use of a smaller fuse to protect the motor, although it also acts to cut down any current surges which might result from rapid fluctuations of the trolley potential.

The motor is a double-commutator machine, each armature winding operating on 750 volts. The set is of two-bearing design with one ball bearing and one roller bearing, the latter to allow for the slight longitudinal movement necessary. A fan mounted between the generator and motor armature provides for ventilation. The generator is a compound-wound machine, having a rating of 3.5 kw. at 37 volts. For one unit, consisting of motor car and trailer it supplies all of the low-voltage power. The generator on the Illinois Central cars operates at a potential held constant by a carbon pile voltage regulator. The design of the set permits the generator to hold a constant voltage output on any trolley potential from a minimum of 1200 volts to a maximum of 1650 volts. The weight of the motor-generator set is 1300 lb.

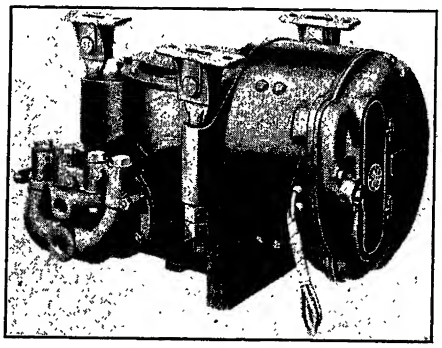

Fig. 9—1500-Volt Air Compressor

On the multiple unit cars of the Delaware, Lackawanna & Western 3000-volt electrification, a dynamotor generator set is used. In general mechanical construction, this is similar to the motor-generator set described. The motor in this set, however, has a dual function, in that it supplies as a dynamotor a potential of one-half trolley voltage for the operation of the 1500-volt air compressor. The output of the dynamotor is 7 kw. at 1500 volts. The control generator will deliver 4.5 kw. at 40 volts at any trolley potential from 2200 volts to 3500 volts. With the larger set and operating on 3000 volts line, an additional resistance of 48 ohms is connected in series for starting. The starting is entirely automatic, being so arranged that when the machine is connected to the line, both the permanent resistance (13.5 ohms) and the starting resistance (48 ohms) are in circuit. As the dynamotor approaches full speed, the generator voltage is built up; this energizes a magnetic contactor, which cuts out the starting resistance. On an interruption of line potential, when the motor slows down to approximately 40 per cent of the normal speed, the voltage of the generator will be sufficiently low to open this contactor and re-insert the starting resistance in the circuit. It was also found advisable to interlock the compressor starting contactor so that the compressor load would not be thrown on the dynamotor until it was practically up to speed. This dynamotor generator runs at a normal speed of 1250 rev. per min., and weighs approximately 2650 lb.

The dynamotor has four brush holders per commutator. The machine is of self-ventilated type, having a fan on the generator end which draws the air through the machine from the dynamotor end. A mechanical air cleaner, consisting of a fan so arranged as to throw out by centrifugal action any dirt that is in the cooling air, is mounted on the dynamotor end of the set.

The machine is supported on the car underframe through special rubber mountings so constructed that the resilience is obtained by having the rubber in tension instead of compression. Provision is made so that in the case of failure of the rubber, the support is taken up by the steel bolt.

Air Compressor

This is a standard type of single-stage motor-driven compressor, with a piston displacement of 36 cu. ft. per min., when operating at full load on the 1500-volt potential. A series motor running at 1060 rev. per min. drives the compressor, through a single reduction herring-bone gear, at a speed of 188 rev. per min. The two cylinders have diameters of 5½ in., and a stroke of 7 in. The full-load current approximates 4.4 amperes.

Storage Batteries

These may be of either the lead or nickel alkaline type. The capacity of the battery to be used will be established by the number of hours of lighting desired to be available in case of failure of the power supply. Normally, the battery will be floated across the constant voltage of the generator and will be used to supply power only when the car is in the inspection shop or when some of the small auxiliary circuits, such as the heater contactors, may be supplied from the battery to avoid the necessity of operating the motor-generator set. The conditions of operating the battery are

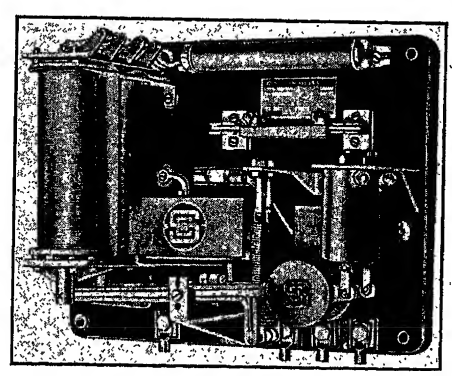

Fig. 10—Generator Voltage Regulator (Top View)

therefore radically different from those existing when the battery is used with an axle lighting generator, in which case the battery must carry all of the lighting load when the train is standing or running less than approximately 15 mi. per hr.

The Illinois Central Railroad cars carry 24 cells of Edison battery of 300-ampere-hour capacity mounted on the trail car. A lead battery of 16 cells of 300 ampere hour capacity will be used on the Delaware, Lackawanna & Western cars. These are mounted on the motor car.

Generator Voltage Regulator

The carbon pile type of regulator so long used by the

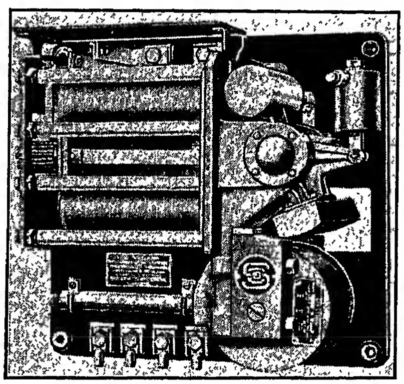

Fig. 11—Lamp Regulator

steam railroads on axle lighting sets has worked out extremely well as a regulator for the multiple unit cars. As the generator runs continuously and the speed variation is relatively small compared with the axle lighting generator, the duty imposed on the regulator is much less than when used with axle lighting sets. This type of regulator will hold the generator voltage constant within plus or minus one volt.

The reverse current relay has a combination of coils which connects the battery in the charging position when the generator potential exceeds the battery potential by one-half volt. With 25 cells of nickel alkaline battery, it will be necessary to run the generator potential between 37 and 40 volts, depending upon how much the battery is discharged in service, and also depending upon the temperature conditions. With 16 cells of lead battery the generator voltage will be set at some value between 34 and 36 volts.

Car Lighting, Headlighting, and Lighting Regulator

The car lighting and the headlights used can very well follow the practise which has become standardized on the particular railroad. It is advisable, however, to insure a high enough intensity of interior illumination to enable the passengers, usually commuters, to read with ease and comfort. Lights should be placed as high as possible and shaded to cut down the glare to a minimum. On electrified zones of steam lines, it has been customary to use headlights which would meet the Interstate Commerce Commission's ruling for locomotives. This requires that a man can be seen 800 ft. in front of the car on a dark night and necessitates the use of a lamp of 100 to 250 watts at 32 volts. The headlight also should have marker numbers on the side as is required for locomotive service. Provision is made to insert in series with the headlight lamp a small resistance when it is desired to dim the headlight, a switch short-circuiting this resistance being placed in convenient location for the motorman to reach.

With the nickel alkaline battery a lamp regulator is required to cut down the normal voltage at which the generator operates, to 32 volts at the lamps. With the 16 cells of lead battery, a lamp regulator will also probably be required as about 34 to 36 volts potential is required to charge the battery. With 15 cells of lead battery 32.5 to 34 volts will be the approximate potential required to charge the battery. In the latter case, if the lights were supplied directly from the battery as during a power interruption, the lamps will operate at slightly under their rated voltage. If automatic train signals are used, consideration must be given to the maximum variation of voltage recommended by the signal manufacturers which may necessitate the use of a 16-cell battery and a lamp regulator.

Discussion

For discussion of this paper see page 1294.

Auxiliary Circuits for High-Voltage D-C. Motor Car Equipments

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Member, A. I. E. E.

and

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Synopsis.—The increasing demand for frequent and rapid transportation on both suburban and other railways has brought to the fore the multiple unit motor car. The steps taken in the development of the auxiliary equipment for the multiple unit motor coach are quite interesting, and have been made the subject of this paper. The first part of the paper is devoted to cars equipped with apparatus for converting the high-voltage d-c. overhead line current to the voltages required for operating standard auxiliary equipment. The second part is devoted to auxiliary equipment suitable for operation on the higher d-c. voltages now being used in more and more electrification projects. Although this paper refers mostly to development work carried out in Europe, it is nevertheless believed to be of interest to American engineers as the basic principles underlying this development are also applicable to American multiple unit cars.

* * * * *

INTRODUCTION

WITH the continued growth of cities and the further expansion of railroad facilities, it will be necessary in the near future for many railroads to consider carefully the electrification of their terminal areas, and this for several reasons, too well known to require repetition in a paper of this scope.

It has been found that for such service the best traction equipment is (multiple unit) motor cars. Moreover, main line railroads are also considering this type of equipment for supplementing locomotive train service. There is no question but that this means of transportation has proved itself to be very economical and efficient. For instance, in order to illustrate the situation, reference may be made to the New York, Chicago, and Philadelphia terminal areas, where hundreds of motor cars are in operation; the first two cases fed by 1500 and 600 volts, direct current, and the last by alternating current.

It is well known that the greatest number of multiple unit cars have thus far been used on subway, elevated, and other city railway systems. Without exception, these systems are operated by 600 to 800 volts, direct current. These equipments, however, will not be considered in this paper, and reference will be made only to motor car equipments for 1500 volts, direct current, and higher.

A further impetus has been given to the use of high-voltage direct curent for railways by the recent development of steel-enclosed mercury arc rectifiers, which are becoming more and more widely recognized, especially because of their high conversion efficiency, small first cost, and lower maintenance requirements. There are several rectifier installations for voltages of 3000 (some of which are tabulated below), while rectifiers are in operation at voltages as high as 13,000.

In recent years several suburban electrifications using motor cars almost exclusively have been carried out with direct current at voltages of 1500 and higher. Many electrifications of suburban lines have been undertaken using direct current at voltages as high as 3000, and one line in particular was electrified and has been in continuous operation for about ten years with 4000 volts, direct current.

In these facts is found our justification for giving a brief outline of the development of the auxiliary apparatus which play such an important part in connection with high-voltage motor cars or multiple unit motor cars.

Experience has shown that it is possible to build electrical equipment for passenger motor cars for 1500, 3000, and even 4000 volts (as mentioned above) with perfect safety to the passengers as well as to the operating personnel.

There is one point on which we wish to touch here, and that is the relation between the multiple unit operation of a car and its operating voltage. There is no direct relation whatever between these two things. This is especially true for control systems where the switches or contactors for the power and speed regulation of the cars are mechanically operated by a cam shaft or by some other mechanical means. A well developed and tested electropneumatic or straight electric multiple unit control system may be used to drive a cam shaft operating either a 600-volt or a 3000-volt switch group. Such switch groups are often manually operated, as will be seen later. The overhead voltage of a system, however, does make a difference as to the way energy is produced for the operation of the control system. Here we naturally have different solutions for 600-volt, 1500-volt, and 3000-volt systems.

For the speed regulation of the vehicles either unit switches, operated electrically or electropneumatically, or cam-shaft driven switch groups are utilized. We favor the latter because an absolute mechanical interlock is maintained between the various switches, thus considerably reducing the possibility of failures. Again, a cam-shaft switch group can be operated by various

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

30-95

drive systems, such as pneumatic drives controlled by magnet valves, electric motor drives, or by manual operation with mechanical transmission from the engineer's compartment to the power controller. This last system is used very extensively in European countries,—especially in Italy where a considerable number of smaller railway systems have recently been electrified with high-voltage d-c. systems, using in most cases mechanically and manually driven controllers.

Some of the recent d-c. main line electrifications using motor cars for 1500 volts or higher voltages on the overhead line are the following:

Railroad	One-hour rating at wheels Hp.	Voltage
In the U. S. A.		
Illinois Central R. R.	965	1500
Chicago, South Shore & South Bend R. R.	....	1500
Piedmont & Northern R. R.	....	1500
Delaware, Lackawanna & Western R. R. (under construction)	885	3000
In Canada		
Canadian National Rys.	575	2400
In Australia		
Suburban Electrifications in Melbourne and Sydney	720 and 560	1500
In India		
Great Indian Peninsula Ry. (Bombay)	1100	1500
Bombay, Baroda & Central India R. R.	....	1500
In Java		
Java State Rys.	450	1500
In Japan		
Japanese Government Rys.	536	1500
In Holland		
Netherland State R. R.	800	1500
In France		
Midi Ry.	700	1500
Paris-Orleans Ry.	1000	1500
In North Africa		
Moroccan Rys.	700	3000
In Spain		
Spanish Northern Ry.	920	1500
In Switzerland		
Nyon-St. Cergue-Morez R. R.	385	2200
Chur-Arosa R. R.	385	2200
In Italy		
Pinerolo-Perosa-Argentina R. R.	330	2200
Biella-Oropa R. R.	380	2400
Biella-Valle Mossa R. R.	340	2400
Pescara-Penne R. R. (under construction)	380	2600
Spoleto-Norcia R. R.	400	2600
Roma-Ostia R. R.	362	2600
Fermano-Porto-St. Giorgio-Fermo Amandolo R. R. (under construction)	400	2600
Sangritana R. R.	400	2600
Arrezo-Sinalunga R. R. (under construction)	580	3000
Vicenza-Chiampo R. R. (under construction)	580	3000
Dolomiten R. R. (under construction)	380	3000
Norte-Milano R. R.	730	3000
Torino-Cirie-Valle di Lanzo R. R.	388	4000 (4700)
In Austria		
Peggau-Uebelbach R. R.	....	2200

It is noticeable that especially in Italy the railroads are more and more employing high-voltage direct current. During a recent trip to Europe one of the authors received the information that the line voltage on the Torino-Lanzo Railroad for some time had been steadily raised and is now being maintained at about 4700 volts at the substation. This was done in order to increase the speed of the trains somewhat. Apparently the traction motors, as well as the line and substation equipment, are able to work continuously at this voltage. This particularly high-voltage traction system has been in operation for about ten years, and from the beginning no serious troubles have been encountered.

Most of the above-mentioned railroad systems that are operated at voltages higher than 1500 do not make use of multiple-unit operation of cars, but are equipped with manually operated cam-shaft controllers. It is only in recent years that multiple-unit operation has been employed on motor cars at voltages higher than 1500. The very first 3000-volt d-c. multiple-unit motor car operation was put in service during the year 1929 on the lines of the Norte-Milano Railroad in Italy. It is probably not well known that almost all high-voltage d-c. railroad electrifications in Europe, especially those for 2000 volts and higher, were carried out by the Brown Boveri companies.

Many of the lines enumerated above are not of large size so far as trackage and number of cars are concerned; especially when compared with North American railroads. Nevertheless, the basic studies had to be made; the development was undertaken, and in all cases the electrifications have proved to be a success.

This paper will be divided into two parts; the first dealing with the power supply for the auxiliary circuits using high-voltage to low-voltage conversion equipment, a system which is exemplified by two typical lines—the first ever built for this type of equipment; the second part will describe in detail the development of auxiliary equipment for voltages equal to those of the overhead distribution systems.

I. Auxiliary Circuits Supplied by High-Voltage to Low-Voltage Conversion Apparatus

There are several circuits requiring electric energy in a motor car in addition to the main motor circuit. Provision must therefore be made to supply the various auxiliary circuits with the proper voltage.

The following are the auxiliaries dealt with in most cases:

a. Control system. Power for the operation of relays, magnet valves, contactors, reversers, etc.

b. Pneumatic system. Compressed air is used on almost all electric vehicles for the operation of various apparatus, for the air-brakes, whistles, sanders, etc. Frequently the brakes are vacuum operated.

c. Lighting of vehicles.

d. Heating of vehicles.

e. Other auxiliary power circuits, such as for blower motors for traction motor blowers, if they are necessary, etc.

f. Automatic train control, if used.

There are several ways in which the above power demands can be taken care of. The best way to show what developments have been made in the art since the first high-voltage motor cars were placed in regular operation back in 1914 is to analyze some of the early

electrifications and compare them with those being made today.

The insulation problem naturally is of the utmost importance in high-voltage d-c. machines, particularly when it comes to machines of small output. Very careful work during the manufacturing processes, and careful inspection once the equipments are in service, are necessary. When the first high-voltage motor cars were built, neither the manufacturers nor the operators thought it possible to operate satisfactorily, direct from the overhead line, as is being done today, almost all the auxiliaries. These early cars therefore were equipped with large motor-generator sets, suspended underneath the floor of the cars. These motor-generators had to be of capacity ample to furnish power to the air compressors, the heaters, the lights, and for the control system in general.

Typical examples of such equipment are the cars operating on the lines of the Nyon-St. Cergue-Morez, and the Chur-Arosa railroads, in Switzerland. The first of these two lines has been in operation since 1914; the second since 1916. Both are working with 2200 volts, direct current. The Chur-Arosa line connects the end-station, Chur, of the Swiss Federal Railways with the well-known sport and recreation resort Arosa. Most of the trackage of this system is on heavy grades. (Over a length of 11 mi. the average grade is 6 per cent; exactly 50 per cent of the entire line consists of curves, and 28 per cent of the entire line consists of curves of 32 deg., *i. e.*, radius of 179 ft.) To take care of its passenger traffic this railroad uses motor cars only. Each car is equipped with four motors having a combined one-hour rating of 400 hp. Speed regulation of the car for motoring as well as during electric braking is obtained by means of a manually operated cam type controller. This applies to all cars of the Chur-Arosa Railroad., as well as to those of the Nyon-St. Cergue-Morez line. The latter are also rated at about 400 hp. All motor cars of both systems are equipped with motor-generator sets of 40-kw. continuous rating. This motor-generator furnishes power for all auxiliaries. The generator of this converting set furnishes power at 300 volts, which is used for the following purposes:

a. Motor of vacuum pump for air-brake system (approx. 4 kw.). The brakes in the motor car and the trailers are regulated by means of this vacuum brake system.

b. Motor of air compressor (approx. 3 kw.). This air is needed for the pneumatic operation of the pantograph current collectors, the main switch (line switch), the reverser of the traction motor circuit, and the pneumatic rail brakes. In the system of rail brakes used on these cars a brake-shoe is forced against the head of the rail by means of compressed air. Such rail brakes are very extensively used on railroad systems where speeds are comparatively low but where heavy grades are encountered. Four rail brake-shoes are used per car. The brake-shoes are fitted with carborundum blocks which are employed to obtain a high coefficient of friction. The cylinders operating these brakes are so dimensioned that the full braking force is exerted with a pressure of about 14 lb. per sq. in. A special reservoir is provided for the rail brake equipment; it is supplied with air at a higher pressure and therefore allows of working the rail brake for a longer period of time in case the contact line voltage should fail. Rail brakes give excellent service, particularly under bad traction conditions such as in thick fog, or when fallen leaves or ice cover the rails. Under those conditions, the rail brakes are applied lightly and serve to clean the rails and thus improve adhesion.

It may be of interest to note that these cars are equipped with four entirely independent brake systems; namely, hand brakes, electric resistance brakes (using the traction motors as generators, the energy generated being absorbed by resistances), vacuum brakes, working on the wheels of the trucks, each of which is equipped with four brake-shoes, and pneumatic carborundum rail brakes, as described above.

In normal operation and on easy grades the electric resistance brake is used to control the car speed, and the vacuum brake is applied for bringing the car to a standstill. If trailers are used, and especially on heavy grades, the trailing cars are retarded by means of the vacuum brakes, while the motor car is braked only electrically. In emergency cases, both air brakes (rail brake and vacuum brake) are applied, and the electric resistance brake may be used on the motor car also.

c. Lighting and heating of motor car and trailers (approx. 33 kw.). The heating elements are direct-connected to the 300-volt d-c. auxiliary power system, by means of snap switches. Twenty-two heaters are installed in each motor car, consuming a total of about 18 kw. About 11.5 kw. are available for the trailing cars and about 2.5 kw. for lighting purposes. Three 100-volt lamps are always connected in series, and 10 such circuits, giving a total of 30 lamps per car, are installed. The power required for these lamps amounts to about 1.5 kw.; approximately 0.5 kw. is therefore available for lights in trailing cars.

The motor-generator set of the cars under consideration consists of a motor with single commutator, wound for direct-connection to the 2200-volt overhead line. The generator, as mentioned before, furnishes 300-volt direct current. Fig. 1 shows a motor-generator set as used on the above-mentioned cars.

Motor-generator sets of later design are equipped with an additional small exciter which is especially provided to keep the generator voltage constant with varying loads and with varying primary voltages. Such a motor-generator set for an output of 1.5 kw. is shown in Fig. 2. Similar converting sets for outputs ranging from 1.5 to 40 kw. and secondary voltages from 40 to 500 volts, have been built in large numbers for primary voltages up to 3000. Fig. 3 shows a section

through such a converter set, but having no auxiliary generator.

Fig. 4 shows one of the Chur-Arosa motor cars. The operation of the line switch, the pantographs, and the switch for the motor-generator are controlled by a

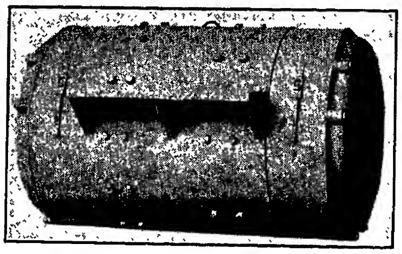

FIG. 1—MOTOR GENERATOR, 2200/300 VOLT, 40 KW.

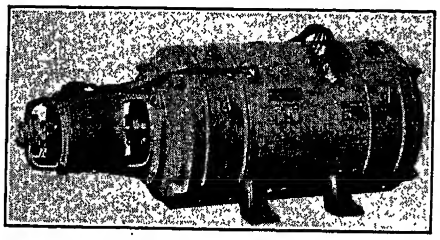

FIG. 2—MOTOR GENERATOR WITH AUXILIARY EXCITER, 3000/48 VOLTS, 1.5 KW.

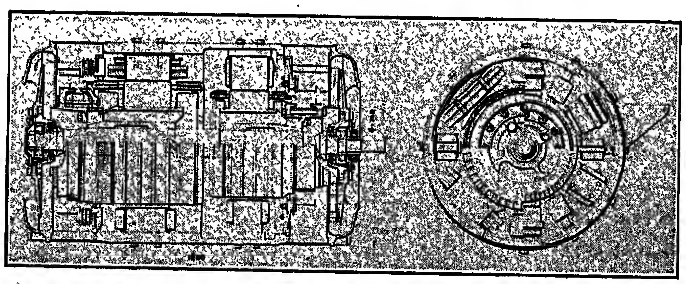

FIG. 3—SECTION THROUGH 40-KW. MOTOR GENERATOR, 2200/300 VOLTS

FIG. 4—MOTOR CAR OF THE CHUR-AROSA R. R., SWITZERLAND, 385 HP., 2200 VOLTS

single valve located in the driver's desk. This valve has three positions: in the first, the pantographs are raised by compressed air; the second closes the switch for the motor-generator set; and in the third position, air is applied to the closing cylinder of the line switch. All three operations are accomplished by air controlled directly from the driver's desk, and without any electric wires whatsoever. So far as experienced, mechanical operation of the main controller, and pneumatic operation of the apparatus mentioned above, results in the minimum amount of maintenance costs of any system

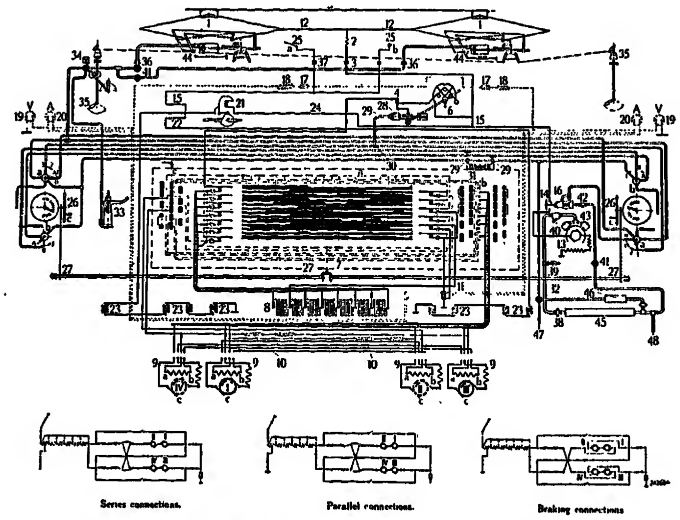

FIG. 5—DIAGRAM OF THE ELECTRIC AND PNEUMATIC EQUIPMENTS OF A MOTOR COACH

1. Pantograph current collector
2. Choke coil
3. Roof insulator
4. Overload release
5. Contact line
6. Main switch
7. Main controller
   a. Main drum
   b. Reversing drum
   c. Motor cut-out drum
8. Starting and braking resistances
9. Traction motors
   a. Field winding
   b. Interpole winding
   c. Rotor
10. Protective resistance
11. Ammeter shunt
12. Disconnecting switch
13. Compressor motor
14. Compressor governor switch
15. Fuse for compressor motor and heating current for trailers
16. Compressor governor
17. Fuse for voltmeter
18. Series resistance for voltmeter
19. Voltmeters
20. Ammeters
21. Heating switch
22. Fuse for heating circuit
23. Heaters
24. Main fuse for heating circuit
25. Rod coupling
   a. Rod
   b. Contact sockets
26. Dummy controller
   a. Valve for current collector and compressor governor
   b. Operating valve for the reverser
   c. Control handwheel
27. Mechanical drive of main controller
28. Pneumatic drive of main switch
29. Cut-out cocks for pneumatic drive of reverser
30. Change-over valve
31. Pneumatic drive of reverser
32. Three-way cock
33. Hand pump
34. Interlock
35. Retaining device
36. Roof insulator for compressed air
37. Roof insulator for heating current
38. Non-return valve
39. Safety valve
40. Oil separator
41. Air release cocks
42. Dust filter
43. Air compressor
44. Throttle valve
45. Main air reservoir
46. Auxiliary air reservoir
47. Air pipe to whistles and sanders
48. Air pipe to brakes

of control. This system, however, is not suitable for multiple unit motor car operation, but has shown excellent results on equipments of the type just described.

Fig. 5 is a diagram of the electric and pneumatic equipment of a motor car. Fig. 6 shows a dummy master controller for a control system as described above.

II. Development of Auxiliary Equipment Operating at the System Voltage

It was soon realized that it was not economical to equip all motor cars with large motor-generator sets as on these first high-voltage electrifications; larger compressors also had to be used, particularly when the outputs of the cars kept increasing, and in many cases higher outputs were necessary due to the fact that more trailing cars which required greater power for heating and lighting were pulled by the motor cars. In other words, in cases where before 40 kw. were sufficient for the auxiliaries, it was now necessary to provide from 50 and 60 kw.

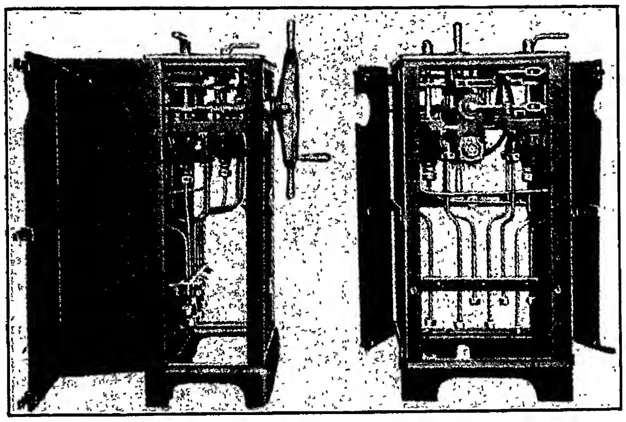

Fig. 6—Dummy Controller with Built-In Valves
Side and rear views, open

a. Compressor Motor. High-voltage auxiliary motors were then developed and first employed in connection with the air compressors. Such a motor compressor for 1500-volt d-c. operation is shown in Fig. 7. The compressor is direct-connected to the motor without any gear reduction. The motor shown is designed to furnish about 10.8 hp. The compressor delivers about 42 cu. ft. per min. at a pressure of 112 lb. per sq. in. Hundreds of such compressors are in operation on various railroad systems. Today compressor motors are being run directly on the 3000-volt trolley lines. Most of the motor cars are equipped with one compressor only, which means that the entire line voltage has to be cared for by one motor.

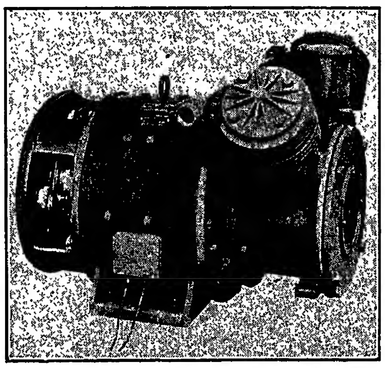

Fig. 7—Motor Compressor for 1500 Volts, Direct Current

As a consequence, the motor-generator sets could be considerably reduced in size. The sets used today average from approximately 1.5 to 2.5 kw.; the rating naturally depends upon the requirements, which differ for the various equipments.

b. Heating Circuit. Parallel with the development of high-voltage auxiliary motors the development of heaters for high-voltage d-c. circuits was undertaken, with the result that for a great number of years, car heaters have been direct-connected to circuits of 3000 volts and higher with no difficulty in service nor danger to the passengers; in fact, experience shows that 3000 volts are no more dangerous than 1500 volts. As early as 1920 there was an undertaking which at that time was considered very risky, and which was not duplicated for many years. This was the connection of car heaters direct to a 4000-volt d-c. system. The Torino-Lanzo-Ceres R. R. Co. in Italy, which operates its system at that voltage, had the courage to undertake what was then believed impossible. It proved to be a complete success, and up to this time not a single accident caused by the heating system has been reported, although the line has been in service for 10 years, and in spite of the fact that during the last two years the line voltage has gradually been raised to about 4700 volts, as mentioned previously.

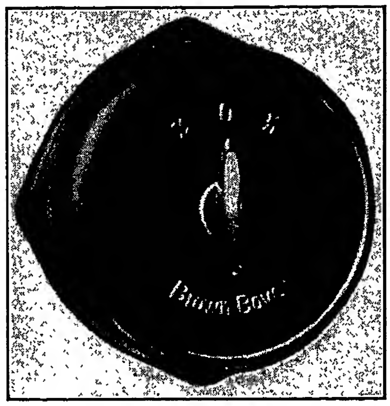

Fig. 8—Turn-Button Switch for Heating Circuit

We are thus not far from the d-c. systems of 5000 volts which were once predicted.

Heating circuits in high-voltage d-c. equipment are utilizing control switches of new design. Such switches are normally located under the car floor or in special compartments provided inside the car body. Special switches that can be located inside the car, accessible to the passengers and the train crew, have also been developed. They are of a very compact design and for a smaller interrupting capacity. These are ordinarily used for the disconnection of branch circuits, and are hand operated. Such a switch for 2600 volts, direct current, and about 5 kw. interrupting capacity, suitable for mounting inside the passenger compartment, is

shown in Fig. 8. This switch, besides being of very small size, is quite neatly designed, and so far as appearance is concerned, can easily be located inside of a passenger car.

The heating of several cars in a train from a motor car naturally requires special couplings between the cars. Various couplings to solve this problem have been

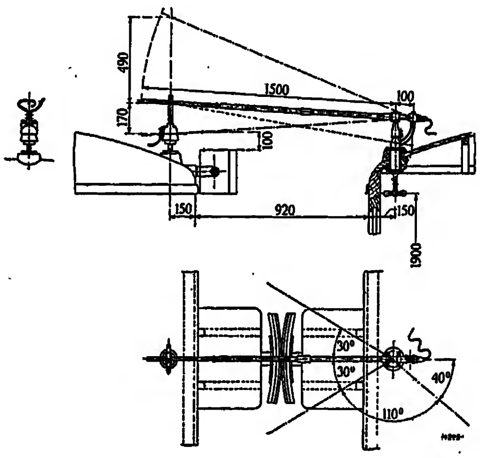

Fig. 9—Rod Coupling for Heating Circuit

designed. In many countries connectors located on the roof at the ends of the cars have been used. Such a coupling is shown in Fig. 9. The comparatively small currents taken by car heating systems at high voltages can readily be handled by couplings of such a design. About 15 to 20 amperes can be carried by a roof coupling of this type, the cost of which is quite low. If the cars separate, the movable part disengages easily, and the contact rod of the car, which in the coupled position reaches over to the other car and engages in a catch,

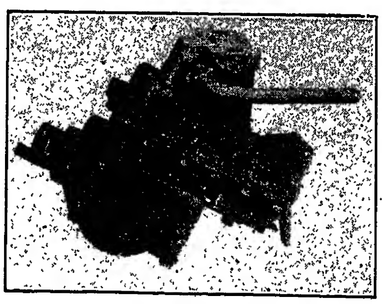

Fig. 10—Train-Heating Coupling for 400 Amperes 3000 Volts, D-C. or A-C.

automatically turns back to its uncoupled position by making a turn of 90 deg. In this position it does not project over the end walls of the car, and cannot be reached by any passengers or the crew. The turning of the coupling rod to engage with the next car is accomplished by means of an insulated handle fastened either outside the car end wall or operated from inside the end vestibule of the car. It might be of interest to know that this type of coupling is often used also for the connection of lighting circuits between cars. For large current ratings, the above-mentioned coupling naturally is not suitable, and heavier couplings had to be developed. Such couplings are in most cases hand operated. Their general appearance is reminiscent of the control-current couplings extensively used on multiple-unit car equipments.

It is, however, quite a different task to build a coupling for a few amperes only, as is the case with couplings for the control current, than it is to build one that is able to carry 300 to 400 amperes continuously. Heating couplings of high current-carrying capacities are usually built for one pole only. A coupling designed for 400 amperes continuous current, at 3000 volts, is shown in Fig. 10. It is therefore possible to carry about 1200 kw. at that voltage with a coupling of this type.

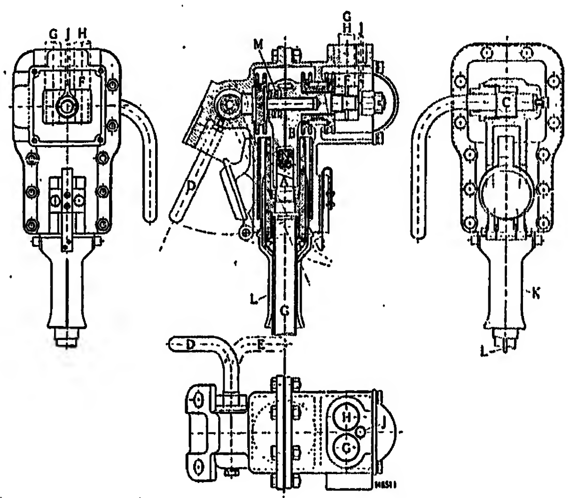

Fig. 11—Coupling Box and Pin for Train-Heating Circuit

A. Contact pin
B. Clamp in two parts
C. Eccentric
D. Eccentric lever in open position (contact loose).
E. Eccentric lever in closed position (contact clamped)
F. Cable terminals
G. Cable connecting the coupling box and pin
H. Cable connecting the two coupling boxes
J. Cable going to the heaters
K. Handle of plug
L. Ground wire
M. Spring
N. Insulating tip

It is desirable not to disconnect the coupling while the power is on. For this purpose an auxiliary contact is provided, by means of which the holding circuit of the heating system main switch, normally located in the motor car, is opened, and the circuit interrupted before the coupling contacts separate. This is done in such a way that the plug of the coupling must be pulled out about one-half inch, whereby the holding circuit mentioned above is interrupted. The plug must now be turned slightly before it can be pulled out, and the main contacts will disengage only after the plug has been moved about one more inch. The time necessary to make these three movements is sufficient to open the main switch before a trainman can uncouple, and any

danger of producing an arc when uncoupling is therefore precluded. Several thousand such couplings are in service at voltages of 1000 to 1500 without having any interlocking contacts at all. A section through such a coupling is shown in Fig. 11. This coupling has no interlocking contact; a coupling with an interlocking contact is shown in Fig. 12.

The heating units themselves are not much different from those for lower voltages, except that their insulation is considerably increased. In most cases, the heating element is embedded in an insulating material (micanite, or something similar); this unit is then fully enclosed in a metal shell, and several of these elements are, in turn, placed within a metal frame of the conventional design by means of a secondary insulation material. The outer housing is usually designed in such a way that it is impossible for any unauthorized person to come in contact with any of the units inside the box. That such a safety measure is

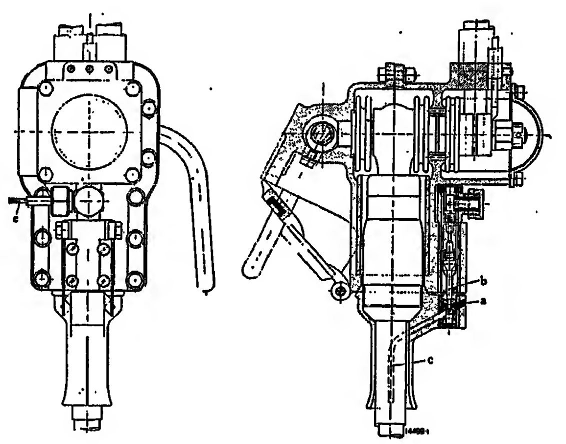

FIG. 12—COUPLING FOR TRAIN HEATING WITH SAFETY INTERLOCKING DEVICE

a. Interlocking contact on the plug
b. Interlocking contact on the coupling box
c. Auxiliary cable

within the range of possibility has been amply demonstrated by the great number of such heating systems as are in operation in high-voltage d-c. motor cars.

From the above it may be seen that the tendency to connect as many of the auxiliaries as possible direct to the high-voltage circuit and do away with all converting apparatus prevails.

c. Control-Current and Lighting Circuits. There are, however, two other circuits which require a power supply and which up to now have not been—and probably never will be—connected directly to the high-voltage system of the motor car. These are the circuits commonly known as the control-current and the lighting circuit.

For a considerable period of time the control current for 600-volt d-c. systems has been taken from the main power circuit, series resistances being inserted into the circuit to permit the use of standard relays, magnet valves, and other apparatus which are necessary for the control of the car, but which are not built for such high voltages. This system is very inefficient, however, and its main disadvantage is that the line voltage must be carried into the master controller, which is very undesirable. In newer equipments, the control circuit and the lights are supplied directly from motor-generator sets with control voltages as high as 300. Still more modern equipment is usually furnished with the control circuit fed from a storage battery in combination with a motor-generator provided for charging the battery, or combined with a battery and a train-lighting axle generator. The voltages employed vary greatly, and equipments are in operation at voltages of 12, 14, 18, 24, 32, 36, and even 48. If motor-generators are used, machines with an output of about 1000 to 1500 watts are sufficient to take care of the lighting and control-current requirements. If the lighting current of several trailers is to be supplied from a motor car, outputs as high as 4000 watts may be required, depending upon the number and wattage of the lamps installed in the cars.

Considerable difficulties were experienced with the high-voltage motor of such motor-generator sets, which, on the whole, gave more trouble than the motors and apparatus of the main power circuits. It was therefore also decided to eliminate this converting machine, and the logical thing to do was to connect the lights and the control circuit to a low-voltage axle generator, as mentioned above.

Evolution of Auxiliary Equipment. Some cars of the Torino-Lanzo R. R. which were placed in operation in the year 1920, were already equipped with such axle generators, to which the lights and the control-current circuit were connected. In this particular case the compressor motor was also driven by this axle generator. The average voltage of this system, which is used in conjunction with a storage battery, is 48 volts. The axle generator is designed for a continuous output of 3.5 kw. at variable speeds ranging from 305 to 1400 rev. per min. The capacity of the storage battery is 145 ampere-hours. The motor of the compressor is built for an intermittent rating of 2 kw. A second, mechanically driven, compressor was also furnished for these cars. This compressor was connected up with one of the truck axles. The system of having two compressors, one for operation also from the battery in case the train is not moving and the other direct-connected to an axle, has decided advantages. On this line, grades up to 3.5 per cent are encountered, but due to the above described system of two compressors it is possible to descend all grades on the line, even when the power fails. As these motor cars are also equipped with the resistance braking system, it is possible to lower the pantographs on the mountain sections when descending the heavy grades, and still have full control over the entire train.

With the solving of the main power and control-current problems, as on the Torino-Lanzo and later

electrifications, solutions have been worked out which have resulted in the present day high-voltage d-c. equipments.

The most modern 3000-volt d-c. traction system, where multiple unit motor cars were utilized for the first time, was put in operation by the Norte-Milano R. R. Co., in Italy, during the spring of 1929. The entire d-c. power supply of this railway system is furnished by mercury arc rectifiers (6000-kw.). The motor cars as well as the trailers of this line are of modern steel-car design. The motor cars are equipped with four axle-suspended motors, each with a one-hour rating of approximately 190 hp. The motors are of the self-ventilated type. The compressor motor is direct-connected to the overhead line, the necessary apparatus, such as compressor governors and contactors, being connected into this circuit at the proper places. The heaters of the motor cars and trailers are also fed from the overhead line and are controlled by means of suitable controllers. Control current, as well as power for the lights, is furnished by the axle generator at an average voltage of about 36. The trailing cars are also equipped with train-lightning generators. The current for heating the trailers, however, is furnished from the motor car, and couplings similar to those shown in Fig. 9 are utilized for the interconnection of the cars.

Protection of the high-voltage auxiliary circuits against excessive currents is accomplished by fuses, these fuses usually being located underneath the floor of the car in boxes especially provided for the purpose, or in high-voltage compartments inside the car.

From the above it can be seen that great contributions toward the development of high-voltage d-c. motor car equipments have been made during recent years. From all indications which we have on this matter and also from the experience gained with equipments now in service, we feel sure that the use of high-voltage d-c. motor cars for passenger transportation in the future presents itself as a technically and economically sound solution of many transportation problems.

Discussion

AUXILIARIES FOR HIGH-VOLTAGE D-C. MULTIPLE UNIT CARS

(C. J. Axtell)

AUXILIARY CIRCUITS FOR HIGH-VOLTAGE D-C. MOTOR CAR EQUIPMENTS

(Marti and Giger)

M. Parodi: The system of electric traction of the French Railroads has been standardized on the basis of direct current at 1500 volts in France, and at 3000 volts on the lines in North Africa.

The general characteristics of the French Railroads involve the use of considerable auxiliary apparatus.

Storage Batteries

The batteries in use are all of the alkaline type. Originally ferro-nickel cells were used. There is a tendency to use cadmium nickel cells, which have the same sturdy characteristics as ferro-nickel and likewise require but little maintenance. This type carries long continued loads as well as the iron-nickel cell, and is not affected by low temperatures. It is operated where stability of electric characteristics and a high degree of retaining the charge under all conditions are of importance, as is the case in connection with supply of locomotive control circuits. It lends itself much better than the iron-nickel cell to trickle charge operation there being no risk of breakage of the internal connections.

On the Paris-Orleans System 72 ampere-hour batteries are always used. Motor cars do not have storage batteries. The locomotives (except one test type) are equipped with a battery of 24 cells connected in series, sometimes on the circuit with two motors used for driving the traction motor blowers, sometimes with two compressor motors, and occasionally with all four motors. This battery supplies only the control and the auxiliary control circuits. The test type of locomotive mentioned above is equipped with a battery of 54 cells, charged from a 1500-72-volt motor-generator set which supplies the control and lighting circuits.

On the Midi System a large number of locomotives are equipped with 85 ampere-hour batteries of 48 cells, charged from the current of the two traction motor blower motors. This battery supplies the control and lighting circuits. The same arrangement applies to another type of locomotive, except that the battery is charged by the compressor motor circuit, or directly from the trolley line, through charging resistance. Another type carries a 132 ampere-hour battery of 64 cells, charged by the current of the compressor and blower motors, or from the contact line through charging resistance. This battery supplies the control and lighting circuits.

On the Paris-Lyons-Mediterranean Railroad a 48-cell 240-ampere-hour battery is used, which is charged by the blower and compressor motor current, and which supplies the control circuit, the lighting circuit and the excitation for the exciters used in regeneration.

On the Algerian Railroads a 48-cell 132-ampere-hour battery is used which is charged by the current of the blower and compressor motors, and which supplies the control and lighting circuits.

An over-voltage relay connected to the terminals of the battery opens either the high speed circuit breaker or the contactor controlling the supply circuit to the battery in case high voltage results from breaking the battery ground connections.

High Tension Auxiliary Apparatus

The motor cars on the Paris-Orleans System are equipped with a motor-generator set of about 3 kw., 1500-72 volts, with a voltage regulator (without battery), for feeding the control circuits and for the lighting of a part of the train—two ends of each motor car.

The locomotives, except two test types, do not have motor-generator sets, the control circuit and auxiliary circuits being fed from a battery. On one type of test locomotive there is a motor-generator set of 3-kw., 1500-72 volts, (with a regulator), charging a battery for supplying the control circuit and the locomotive lighting current; on another type of test locomotive there are two motor-generator sets about 30-kw., 1500-110 volts, with a regulator (without battery) for supplying the control circuits, the locomotive lighting circuits and two motor blower sets which supply air for the traction motors; one is a service set and the other reserve.

A high tension motor-generator set consists essentially of:

1. A 1500-volt motor completely compensated, the armature of which carries two distinct windings each terminating in a commutator (one placed on one end of the armature, with the other on the opposite end). These two armatures are operated in series for 1500-volts.

2. A d-c. shunt generator with auxiliary commutating poles wound for 72 volts. The voltage at the terminals of the set is maintained practically constant by means of a special regulating device essentially comprising of a small shunt motor,

the armature of which is in series with the shunt winding of the generator and the field of which is shunted at the terminals of the generator with a high resistance. The scheme is indicated in Fig. 1. The speed of the small motor is limited by a small fan at the end of the shaft. The voltage at the terminals of the small motor varies according to whether it is excited or not; energizing or de-energizing its excitation is affected by armature *A* or relay *E*. The relay and its vibrating armature constitute a simplified Tyrrill Regulator. The relay *E* is provided with two windings; the first, tapped to the terminals of the 72-volt gen-

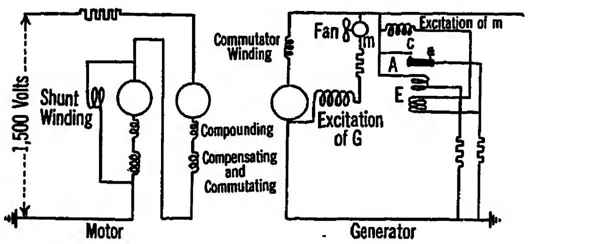

Fig. 1—Special Regulating Arrangement of a Motor-Generator Set

erator, is supplied by a voltage closely proportional to the voltage of this generator; the second, wound in the opposite direction and connected in series with the field winding of the small motor, facilitates the movement of armature *A* and stabilizes the voltage by reducing the difference between the voltages corresponding to the opening and closing of *A*.

These low-capacity, high-voltage, motor-generator sets installed on the Paris-Orleans System have not given good service, for 68 out of 80 equipments have been damaged.

On the motor cars of the Midi Railroad and in Morocco the supply for auxiliary circuits is accomplished by rotary transformers.

A machine has been designed for this purpose to transform direct current of a given voltage to direct current of another voltage. This is composed of an armature carrying two independent windings, each one being connected to its own commutator. One of the windings is a motor; the other a generator. The magnetic circuit is common to the two windings. The electric field circuit carries two windings, one wound in series with the motor windings and the other as a secondary on the generator winding. This type of machine is generally constructed without auxiliary poles, the resultant ampere-turns on the armature at constant load being virtually nil.

If such a machine is used on a direct current locomotive for the production of the low voltage direct current necessary for supply of the auxiliary circuits, there would be poor commutation whenever there is a variation either in the load on the generator or in the voltage of the power supply to the motors. The series and shunt windings present a strong coefficient of mutual induction, and when, for instance, the supply voltage rises, the flux produced jointly by the two field windings follows this change with difficulty. A sudden increase in the current flowing in the motor winding results, which immediately produces an overload on the brushes, and also poor commutation. For this reason Mr. Royer and I were led to develop a scheme to insure good commutation at both collectors not only under normal conditions but under variable conditions produced by changes in the supply voltage or in the load.

Commutation may be improved by providing auxiliary commutating poles, the field circuits of which have two windings, one wound in series with the motor armature and the other in series with the generator armature, producing bucking ampere turns, the former winding being slightly predominant over the other, under normal conditions.

Excellent results are obtained without commutating poles by providing a reactance in the machine circuits as indicated in Fig. 2.

S —Reactance
M —Motor armature winding
G —Generator winding
Im—Inductor winding in series with *M*
Ig —Inductor winding in series with *G*

The current of the motor armature *M* flows through the reactance *S*. For example, when there is a rise of voltage the voltage at the terminals of *S* becomes very high. Since the voltage at the terminals of *I g* is equal to the sum of the voltages at the terminals of *S* and of *G* (circuit *S*—*I g*—*G*), an increase in the voltage in *S* results in an increase in the voltage in *I g* and in the opposite direction; that is, in a direction opposite and equal to that which *I m* produces by induction on *I g*. This is thus counterbalanced, and the inertia which the whole assembly *I g*-*I m* would produce in order to establish flux, disappears. The main flux thus quickly follows the variation in the series ampere turns.

This type of machine has been adopted for general use in the motor car equipment of the Midi Company to transform current at 1500 volts to 72 volts for supply of control and lighting circuits, as well as on the Morocco Railroad Company, where the transformation is from 3000 volts to 120 volts. The power developed on the low tension side may amount to about 12 kw.

Locomotives equipped for electric regenerative braking as used on the Midi System or on those of Northern Africa, are equipped for supplying the low voltage auxiliary apparatus with units consisting of a high tension motor connected to two low voltage generators, one for constant voltage, the other for variable voltage.

The high tension motor is connected to the trolley supply line through permanent resistance as a protection against variations in line voltage, and through two circuit breakers in series, which open on overload following overspeed in the set. This motor has compound excitation with a compensating winding, and a separate excitation, furnished by the constant voltage generator.

The motor circuit includes safety devices for disconnecting it from the line in the event of failure of supply power or overload of the motor.

The constant current generator is of a shunt type, regulated by resistance. It supplies the auxiliary equipment with low voltage power.

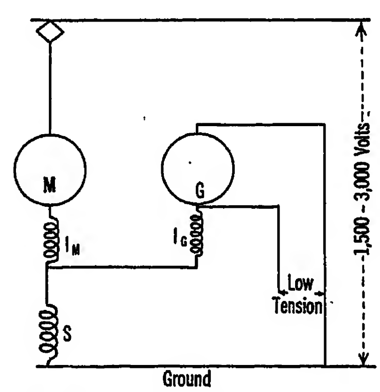

Fig. 2—Parodi-Royer Arrangement

The variable voltage generator plays the part of exciter, for regeneration, its armatures in that case being connected to the fields of the traction motors, functioning as generators. Its excitation is accomplished in part by a winding fed from the constant current generator, the current of which is controlled by means of resistance which regulates the apparatus through electro-magnetic contactors; and in part by an "anti-compound" winding fed from the trolley supply circuit.

When a motor has two field windings, one series and one shunt or independent, the coefficient of mutual induction of these two windings prevents the resultant flux from following the variations in the supply voltage. There may result poor commutation and

sparking, if the supply voltage is high, as is the case in the locomotives of the French Railroad systems.

We can partially remedy this difficulty by tapping the shunt winding at the terminals of the commutator and by a reactance in series with the latter; it is then acted upon by the sum of the voltages in these two parts; that of the reactance being very important at the instant of variation in the supply voltage. In this case a potential is developed in the shunt winding, in the opposite direction to that which is induced in the series winding, and the effect of mutual induction is counterbalanced.

The arrangement invented by Mr. Royer amplifies the compensatory voltage produced in the shunt winding by placing the primary P of a transformer (Fig. 3) in series with the motor armature M and its secondary S in series with the shunt field B. In the accompanying figures where A represents the series field winding, E an exciter and G a generator winding, we have in Fig. 1 the arrangement with a second shunt winding, in Fig. 2 with a second separate excitation winding, while Fig. 3 shows the arrangement with a motor-generator.

This device is in operation on the Paris-Lyons-Mediterranean System locomotives.

Compressors

Two compressor sets are often installed on the locomotives, one being in continuous service while the other is in reserve. Starting is accomplished automatically by a pressure regulator.

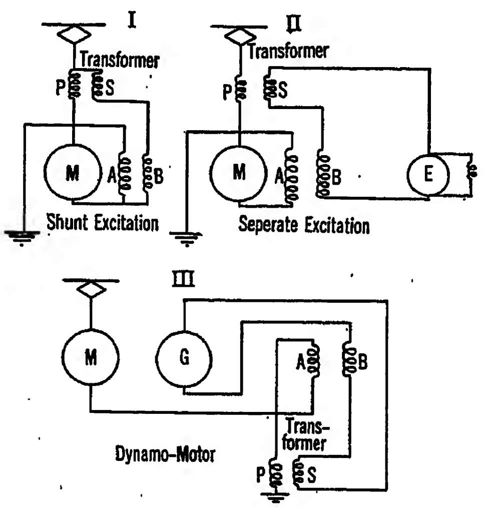

Fig. 3

All compressor motors on the Paris-Orleans System, operate at 1500 volts. The motor cars of that system carry but one compressor, but a connection permits all the compressors to share in the supply of air used by the brakes and the control facilities.

On the Midi System the motors connected to the two compressors operate at 1500 volts on the locomotives which are equipped for static braking. On the locomotives which are equipped for regeneration and on the motor cars, the compressors operate on low voltage power.

On the Paris-Lyons-Mediterranean System the two compressor motors operate at 1500 volts; and in Morocco and Algiers they are fed at low voltage.

There is a tendency to increase the compressor capacity up to 2400 litres per minute (85 cu. ft. per minute) and even to carry three compressors. The use of rotary instead of reciprocating compressors can be foreseen.

The charging pressure is 7, 8 or 10 kg. per sq. cm. (100, 114 or 142 lb. per sq. inch) depending on the type of compressor.

Ventilation of the Motors

On the Paris-Orleans System the ventilation of traction motors on locomotives is accomplished by two blowers (one for each pair of traction motors), each of these blowers being driven by an independent motor operating at 1500 volts; there are thus two independent sets. On one test type there are two sets each consisting of a motor driving two blowers (one for each traction motor). On another test type there are also two groups, each consisting of a motor driving three blowers (one for each traction motor). There is no forced ventilation on the motor cars of that system the motors being self ventilated.

The ventilation of the traction motors on a number of locomotives on the Midi System is accomplished by two sets, each consisting of a motor connected from the 1500-volt circuit through permanent resistance, driving two blowers; there are thus four blowers for four traction motors—one blower for each motor.

Another type of locomotive has two blowers (for the four traction motors) driven by the 1500-volt motor which drives the constant voltage generator; that is, one blower for two motors. On another there are two sets consisting of a 1500-volt motor driving a blower; that is, two blowers for the three traction motors and on still another type each 1500-volt motor drives one blower which supplies the ducts for three motors.

Certain locomotives of the Paris-Lyons-Mediterranean System have two sets of two blowers for the six traction motors. These blowers are driven by 1500-volt motors. On another type of locomotive there are two sets, with one blower each for the six traction motors; that is, one blower for three motors. These blowers are driven by 1500-volt motors.

On the Morocco systems, on certain locomotives there are two blowers for two motors. These blowers are driven by the 3000-volt motor which drives the constant voltage and the variable voltage generators. On other types there are two sets consisting of one motor fed at low voltage by the constant voltage generator which drives two blowers; thus four blowers for four traction motors—one blower for each motor.

There are three blowers for the traction motors, drawing from a central reservoir on the systems of Algeria; that is, three blowers for six motors. These blowers are driven by the 3000-volt motor which drives the constant-current and the constant voltage generators.

On the table next attached are shown figures on the capacity of the auxiliary groups, the blower sets and the compressor sets used on the various types of equipment.

Ventilation of the Cab

There is no provision for ventilating the cab on the French systems. But on the Moroccan and Algerian systems the ventilation of the cab is accomplished by a special blower driven by a low-voltage motor supplied by the low-voltage constant potential generator of the high-voltage motor-generator set.

Heating the Cab

On the Paris-Orleans System this is accomplished by two 800-watt electric radiators mounted in series on the 1500-volt circuit.

On the Midi System there were installed at first 200-watt heaters operating at 120 volts. More recently 200-watt heaters have been installed in series on the 1500-volt circuits. On certain locomotives 750-watt radiators have been installed in series on 1500 volts.

The Paris-Lyons-Mediterranean System heating is accomplished by three 500-volt radiators in series on 1500 volts, utilizing a total of 2500 watts.

On the Algerian Railroads two 200-watt heaters have been installed fed at 150 volts from the constant potential generator of the high voltage motor-generator set.

The same arrangement is used on the Moroccan System.

Electric Heating of Trains

The tendency is to heat the passenger coaches by electric power taken from the contact wire. Some installations have already been made by the Paris-Orleans Company, which is progressively equipping the coaches which are hauled by elec-

tric locomotives. They are using radiators connected directly to 1500-volts. This necessitates a high voltage bus the length of the train. In order to avoid hazard the couplers are equipped with an interlocking device which does not allow them to be opened when there is voltage.

Lighting the Cabs

The lighting circuit comprises:

1. In the interior of the locomotives a certain number of ceiling lamps, a lamp lighting the speed indicators, a lamp for the controller and sockets for inspection lamps.

2. On the outside, the regulation lights on each end of the locomotive.

On the Paris-Orleans Railroad locomotives, (with the exception of a few test types) the outside lights and the interior lamps, except the lamps for the controller and the instruments, are connected in series and in series with resistance on the 1500-volt circuit; the instrument lamps are fed from the 32-volt battery. In the test locomotives the lamps are supplied from the battery or from the low voltage generator of the high tension motor-generator set. On motor cars the lighting is also supplied from the low-voltage generator.

On the other systems, the lamps are arranged in parallel on low-voltage circuits, the voltage of which depends upon that of the battery.

To avoid burning out the lamps by excess voltage caused from undue variation in charging and discharging the battery, when the voltage of each element is greater than 1.05 to 1.8 volts a relay connects the lamp circuit to a reduced number of cells while the battery is being charged. On the other hand, when the battery is being discharged the lamps are supplied by the entire number of cells. This protection has proven very effective.

General Arrangement in the Locomotives

The tendency on locomotives of the French Systems is to avoid as far as possible the installation of cables and to replace them with bare bars. When the installation of insulated wire is necessary, instead of placing the cables in rigid conduit they are installed in flexible conduit, not only inside the cab but under the cab. As to the location of apparatus inside the cab, a central compartment is provided in which all the auxiliary rotary apparatus are installed. This compartment is wide enough to admit a man in spite of the crowding of the apparatus. On either side are cells in which all the appliances (contactors, resistances, etc.) are installed. This arrangement allows easy access for maintenance and the apparatus can be easily removed.

MIDI SYSTEM

Type of locomotive	BB	BB	BB	2C2	Loco. coach	Motor coach
H. P. Continuous	1000	1000	1600	1500	650	500
Hour	1400	1400	1760	2200	800	700
Blower sets						
Number	2	2	2	2		
Motor rating h. p.	10	*	13	10	*	*
Voltage	1500		1500	1500		
Capacity cu. ft./sec	28. (2)	59. (2)	47.	85.		
Compressor sets						
Number	1	1	2	2	2	1
Motor rating h. p.	18.	18.	15.	18.	10.	9.
Voltage	120.	120.	1500	120.	1500	120.
Capacity cu. ft./min	42.5	42.5	42.5	42.5	21.	21.
Charging pressure	100.	114.	100.	100.	100.	
Auxiliary sets (M-G) Number	1	1				
Motor rating h. p. Hour	80.	80.				
Continuous	50.	50.				
Motor voltage	1500	1500				
Constant potential gen. rating kw.						
Hour	22.	22.				
Continuous	12.	12.				
Constant potential gen. voltage	120.	120.				
Variable potential gen. rating kw. Hour	22.					
Variable potential gen. voltage	75.					
Rotary transformers						
Primary voltage						1500
Secondary voltage						120.
Rating (hour) kw						10.

(*Blowers on auxiliary set shaft.)

PARIS-ORLEANS SYSTEM

Type of locomotive	BB	BB	BB	BB	2D2	2D2	2CC2	Motor car
H. P. Continuous	1320	1540	1320	1240	3380	3200	2040	640
Hour	1640	1720	1680	1420	4200	3600	3000	860
Blower sets								
Number	2	2	2	2	2	2	2	
Motor rating h. p.	5.5	9.0	18	13.	16	16	17.3	
Voltage	1350	1350	1350	1350	1350	1350	1350	
Capacity cu. ft./sec	47.	82.	65.	94.	147.	71. (2)	65.	
Compressor sets								
Number	2	2	2	2	2	2	2	1
Motor rating h. p.	12	9.5	12	12	10.8	10.	17.5	12
Voltage	1500	1500	1500	1500	1500	1500	1500	1500
Capacity cu. ft./min	44.	51.	44.	44.	60.	60.	75.	44.
Charging pressure		100.	100.	100.	113.8	113.8	142.2	100.
Auxiliary sets (M-G) No.								
Motor rating h. p. Hour					40.	5.		
Motor voltage					1500	1500		
Const. pot. gen. rating kw. Hour					30.	3.		
Const. pot. gen. voltage					110	72.		

	P. L. M. system	Morocco system			Algerian system
Type of locomotive	1CC1	BB	BB	Motor car	CC
H. P. Continuous	1500	1000	1300	500	2040
Hour	2100	1400	1620	700	2400
Blower sets					
Number	2	2	2		3
Motor rating h. p.	*	*	13.5		*
Voltage			120		
Capacity cu. ft./sec. (each)	104.	64.7	47.		94.
Compressor sets					
Number	2	2	2	1	2
Motor rating h. p.	15.	18	18	9.	15.
Voltage	1500	120.	120.	120.	120.
Capacity cu. ft./min.	21.	21.	21.	21.	21.
Charging pressure	100.	100.	100.	100.	128.
Auxiliary sets (M-G) No.	2	1	1		1
Motor rating h. p. Continuous	50	90.	90.		140.
Motor voltage	1500	3000	3000		3000
Constant potential gen. rating kw. hr. Continuous		16.	39.		22.
Constant potential gen. voltage		120.	120.		120.
Variable potential gen. rating kw. hr. Continuous	15	23.5	23.5		38.
Variable potential gen. voltage	48	130.	130.		
Rotary transformers					
Primary voltage				3000	
Secondary voltage				120.	
Rating (hour) kw				10.	

(*Blowers on auxiliary set shaft.)

Railbonding Practise and Experience on Electrified Steam Railroads

BY H. F. BROWN*

Member, A. I. E. E.

Synopsis.—This paper deals primarily with the development, description, and characteristics of various types of rail bonds used at track joints for traction return and incidentally signal track circuits. It outlines their performance and reasons for their selection on representative electrified steam railroads, which include:

Baltimore & Ohio
Boston & Maine
Chicago, Milwaukee, St. Paul & Pacific
Delaware, Lackawanna & Western
Illinois Central
New York Central
New York, New Haven & Hartford
Norfolk & Western
Pennsylvania
Reading
Virginian

No attempt is made to discuss the track circuit characteristics and requirements for either signaling or propulsion return. Cross-bonding, impedance bonding, and structure grounds are also outside the scope of this paper.

The track construction and maintenance, weight of rail, type of joints, condition of roadbed, ballast, traffic density and frequency, wheel loadings, amount of current to be carried, track signal circuit requirements, etc., all have a direct bearing on the design and proper application of the rail bond, which is thus a problem involving mechanical as well as electrical features.

From the data submitted, an attempt is made to indicate the trend of bond design.

I. Development of Various Types of Rail Bonds

The problem of making a continuous circuit of comparatively low resistance out of a large number of joined conductors such as track rails, has been one which has confronted electrical engineers since the earliest application of electricity to railroading, not only for traction power return, but for signaling. It was evident from the very earliest attempts to utilize the rails as part of any electric circuit that some means would have to be devised to shunt out the high, or at the best, very variable, resistance which the rail joints created. As far back as 1872, wire connectors, or bonds, around the rail joints were devised for track circuits in connection with signaling. Since that date, the problem has had the attention and study of two different groups working along different lines, the street railways and the electrified steam railroads seeking an economic method for providing a low resistance path for currents of large magnitude, whereas the requirements for signaling alone were for relatively small currents.

Channel Pin Type Bond

The earliest type of rail bond was the so-called channel pin type, developed in 1872 by Dr. William Robinson for track circuits in connection with railway signaling. This type has continued in use down to the present time for such circuits, practically without modification. As used for signal bonding, this takes the form of a tapered pin having a channel or groove of the size of the bond wire. A hole is drilled in each rail, usually in the web, large enough to admit the small end of the channel pin. The wire, usually about No. 8 steel, is inserted through the rail, and the channel pin is then driven in, tightly wedging the wire into close contact with the rail (see Fig. 1). This device has been widely used because of its simplicity and relatively low cost. Two separate bonds per joint are generally used to insure reliability.

Later, when electric traction requirements called for heavier wires, the same method, with larger channel pins, was used with some success. With larger wires,

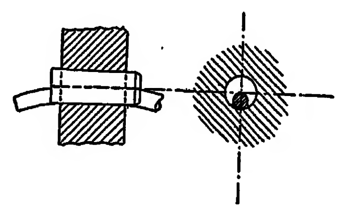

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Fig. 1—Channel Pin Signal Bond

a. Detail of channel pin
b. Double bond of No. 8 wire around joint

however, there is more chance of the pin not completely filling the hole, thus allowing the entrance of moisture, with consequent impairment of contact. The larger bonds were also relatively expensive, since they were made of copper and of course had to span the splice bar. They were also exposed to injury and liable to theft.

Split sleeves or bushings have been devised for these larger wires, as a modification of the channel pin idea, but all such methods are open to the objection of the

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

possibility of moisture entering and causing corrosion between the rail and the pin or sleeve, with resultant increase in the contact resistance. Bonds of this type (see Fig. 2) were always of single solid wire, which was subject to rapid crystallization and ultimate fracture at the entrance to the rail where vibration and movement of the joint proved very severe.

Soldered and Brazed Bonds

The need for greater flexibility with larger capacity conductors, together with the need for a better and more permanent method of contact with the rails, brought about the soldered bond. This type of bond consists of one or more laminated or stranded conductors forged or soldered into a terminal, which in turn

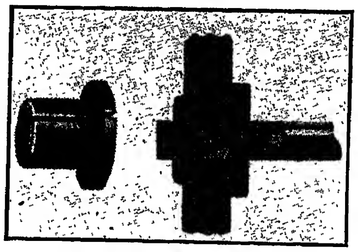


Fig. 2—Solid Wire Bond with Split Sleeve

is soldered or brazed to the rail head, web, or flange, (see Fig. 3) at a point previously cleaned, usually by means of a portable emery wheel. When applied next to the ends of the rails, such bonds are relatively short and inexpensive. Where the splice bar is spanned, they are

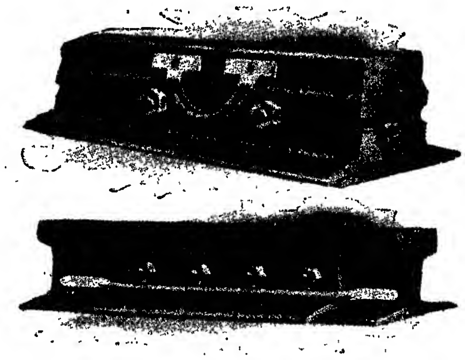


Fig. 3—Soldered Bonds

Top: Soldered terminal bond on ball of tee rail
Bottom: Soldered terminal bond on web of tee rail

obviously more expensive. The labor cost of cleaning and tinning the rail and applying the bond is relatively high for this type of bond.

Brazed bonds are similar in design to the various types of soldered bonds in so far as the terminals are concerned. The refinements which have been made during the past few years to the conductor design and its attachment to the terminals in connection with arc weld and flame weld bonds have also been incorporated in the more recent designs of brazed bonds. The application to the rail differs from soldering, in that a more intense heat is required. The brazing metal melts at a temperature which does not differ greatly from the melting temperature of the bond terminal, thus actually fusing with it and producing a much stronger union with the rail than is obtained with a soldered joint. This is a very superior method of attaching bonds to rails, from the electrical as well as the mechanical point of view. A typical installation is shown in Fig. 4.

The brazed type of bond has a distinct advantage over other types of heat applied bonds, in that it is applied at a definite temperature which is not dependent upon the skill of the operator. It has the disadvantage, in addition to the same preliminary preparation of the rail surface as with soldered bonds, of requiring special equipment which must be attached to the rail during the process of applying the bond, thus offering an obstruction to traffic, and usually requires electric power of special characteristics, not always available on some electrified systems, for the necessary heat.

Stud Terminal Bonds

A. Compressed Terminal. Bonds of this type consist of one or more laminated or stranded conductors

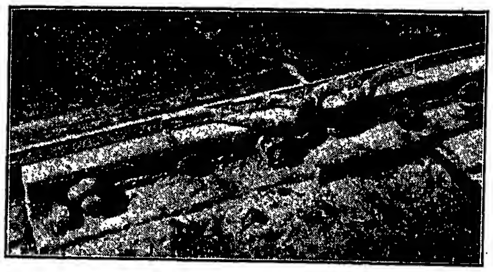
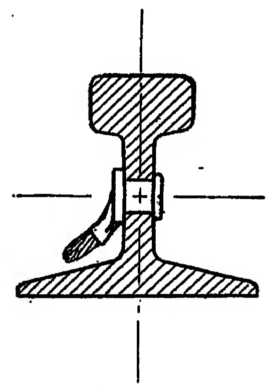


Fig. 4—Double Brazed Bonds (L. I. R. R.)

forged or welded into a solid terminal at each end, having a cylindrical stud, ¾ in. to 1 in. in diameter, and slightly longer than the thickness of the rail web or flange (see *A*, Fig. 5). The stud is introduced into a slightly larger hole drilled into the rail web or flange, and then compressed by heavy pressure applied to both ends of the stud, to completely fill the hole, with a head or shoulder on each end to seal the joint. If the holes have been freshly drilled or reamed, and contain no grease or moisture, a very low resistance contact can be made between the rail and the bond, which has a fair degree of permanence. On the other hand, if improperly or carelessly applied, they are subject to all the disadvantages of channel pin bonds. The necessary compressing equipment is rather cumbersome and requires considerable time to apply to the bond and to compress the terminal. An obstruction is offered to traffic while the apparatus is in place on the rail, which is a serious disadvantage. Short, inexpensive bonds of this type were designed to be applied at the ends of the rails, removing the splice bars for their application (see *A*, Fig. 6). Longer, more expensive bonds were designed to span around the outside of the splice bar (see

B, Fig. 5). Either design resulted in a fairly expensive bond, in place, considering material and labor costs.

A modification of the compressed terminal type bond which was formerly used to some extent, but which has



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b

FIG. 5—COMPRESSED STUD TERMINAL BOND

a. Detail of terminal
b. 4/0 stranded
Exposed type used on the New Haven 1900-1911

now practically gone out of use, was the "twin stud terminal" type, designed to be applied to the head of the rail (see Fig. 7). In this type the terminal studs were smaller in diameter (about ½ in.) than the usual compressed terminal, two on each terminal, and of definite length. Two holes were drilled to the proper depth and spacing in the side of the rail head, and then an undercut ring or thread was made in each hole. The terminal studs were then forcibly hammered and

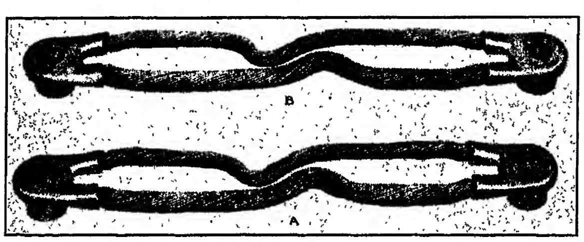


FIG. 6—DUPLEX CONCEALED TYPE STUD TERMINAL BONDS

a. Compressed stud terminal
b. Pin expanded stud terminal

expanded into these holes. The labor cost of installing such bonds was relatively high.

Combinations of stud type bonds with terminals also soldered to the rail have been extensively used, especially in street railway work. Their chief advantage was the high mechanical strength of the stud terminal with the low permanent resistance of the soldered connection. This was offset to a large extent by the greater cost of installation.

B. Pin Expanded Stud Terminal Bonds. This is a refinement of the compressed stud terminal design, in that the stud terminal has an axial hole to take a short

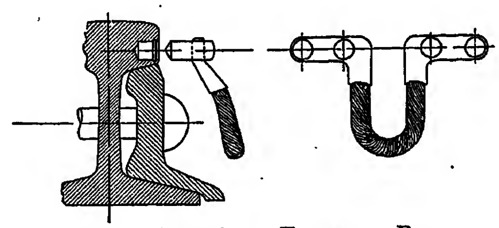


FIG. 7—TWIN STUD TERMINAL BOND

steel plug tapered on one end, having a diameter larger than the hole. The rail is drilled or reamed, as in the case of the compressed terminal bond, and after the bond terminal is in place a hard steel tapered drift pin is driven through the hole in the terminal, expanding it

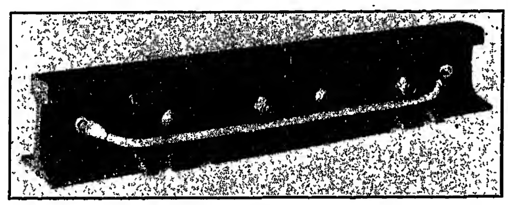


FIG. 8—PIN EXPANDED STUD TERMINAL BOND, EXPOSED TYPE

to completely fill the hole in the rail. The hole in the terminal is then filled by driving in the short steel plug, which is of slightly larger diameter than the drift pin (see Fig. 8).

This type of bond has proved very satisfactory in extensive use, chiefly because of the flexibility of design

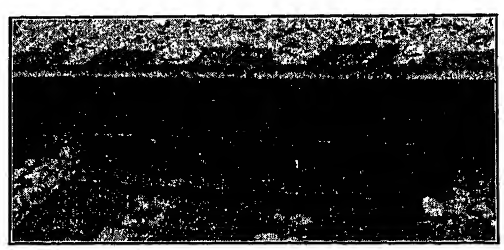


FIG. 9—PIN EXPANDED STUD TERMINAL BOND, CONCEALED TYPE. (N. Y. C.)

and ease of application. It has been used in all lengths and capacities, from small signal bonds up to the largest sizes of traction bonds, applied to either the flange or web, concealed beneath the splice bars as in Figs. 9 and 6B, or extending around the outside as in Fig. 8. The chief disadvantages of this type are the uncertainty of contact, especially if the holes in the rail have not been previously freed from rust, moisture, or grease, and the relatively high cost of the bond itself and the cost of drilling or reaming the holes in the rails.

A modification of the pin expanded stud terminal bond which is extensively used consists of a stranded conductor having the forged-on terminal on one end only. The other end of the strand is tinned, and is soldered into a separate pin stud terminal, (see Fig. 10) after having been placed in position beneath the splice bar, after which both terminals are applied to the rails in the usual manner. A crimp or bend is provided in the strand, between the first and second bolt of the joint, to allow for rail expansion, and to prevent removal of bond without taking out the first bolt, which is removed for the installation of the bond. This type of bond has given a high degree of satisfaction on one or two electrified railroads because of its ease of installation (since no splice bars need be removed), its concealed and protected location beneath the splice bar, and its high salvage value because of its possibility of re-application. A disadvantage is the additional cost of the soldering operation, although this is easily done since the wire and terminal are already tinned. It is obvious that separate terminals of this type can be used on each end to make up such bonds in the field of any length desired from stranded copper wire.

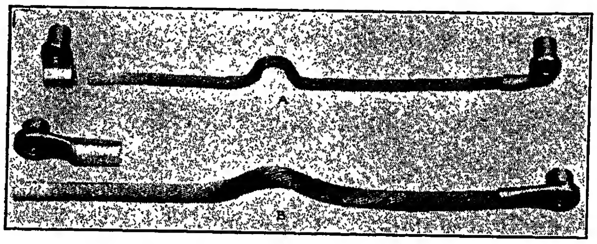
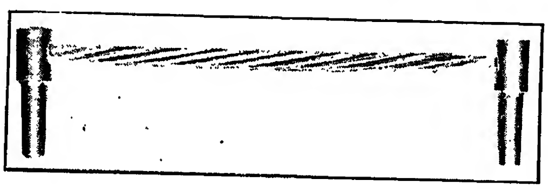


FIG. 10—PIN EXPANDED STUD TERMINAL BOND, WITH SEPARATE SOLDERED TERMINAL

a. Similar to bond used on N. & W.
b. Similar to bond used on Virginian



a

b

FIG. 11

a. Taper pin terminal signal bond
b. Taper pin terminal bond in place on rail joint (double conductor type used experimentally on P. R. R.)

TAPER PIN TERMINAL BONDS

A type of bond developed primarily for signal circuits, but which has been used to some extent on multi-track railroads electrified with high-voltage alternating current (where there are consequently comparatively low values of rail return current) consists of a tapered steel pin approximately 3/8 in. in diameter, having an enlarged head, into which are welded one or more stranded conductors, long enough to span around the splice bar (see Fig. 11A). For signal circuits, the conductors are usually of 3/8 in. 7-wire galvanized or copper covered steel strand. For traction circuits the double strand wires are of copper, or a combination of copper and steel wires (see Fig. 11B).

This type of bond is easily applied, requiring but a small (3/8 in.) hole drilled in the web of the rail just outside the splice bar, into which is forcibly driven the taper pin terminal.

The length and exposed location of these bonds give them the disadvantage of liability to injury from dragging equipment or otherwise, or to theft if of copper; and if they once become loose they are not easily kept tight without renewal of bond.

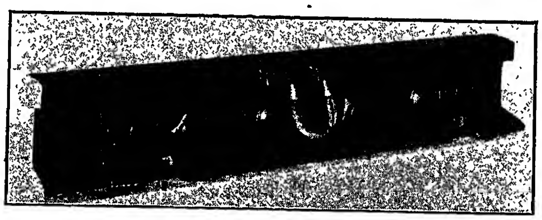


FIG. 12—TYPICAL ARC WELD BOND—U-TYPE

HEAT APPLIED BONDS

Mention has already been made of the various types of bonds applied to the rails by means of solder. Such bonds had very good contact resistance characteristics, but the soldered joint was mechanically weak, and was very often broken by the constant vibration. Hard soldering, or brazing, produces somewhat better strength characteristics, but requires a higher temperature of application, which under some conditions may be difficult to obtain. Early attempts proved the entire feasibility of arc-welding the bonds to the rails, using either the carbon arc or a metallic electrode, and taking the power from the contact conductor through suitable controlling apparatus. With the subsequent development and improvement of portable electric welding equipment, there have been many types of bonds designed for application in this manner. The latest designs (see Fig. 12) are very short, for application at the ends of the rails, and are consequently of relatively low cost. The cost of application, with properly qualified labor, is also relatively low, making this type of bond a very desirable one from an economic standpoint. It has a fairly high service performance record, although subject to the usual hazards due to its location

on the rail. Where electric power of suitable characteristics is available for such purpose, this type of bonding seems to justify serious consideration.

Flame Weld Bonds

With the rapidly increasing use of the oxy-acetylene torch for cutting and welding processes, both in shop and in field, within the past few years, and with the increasing use of this tool by track maintainers to build up worn rail ends at the joints, frogs, and switch points, it was only natural that this method should be used for applying bonds similar to those designed for arc welding; and accordingly new designs have been made especially for this process, both for signal and for traction bonds. There was naturally some question on the part of those responsible for track design and maintenance regarding the effect of such intense local heating on the structure and performance of the rail. After exhaustive study the Rail Committee of the American Railway Engineering Association reported in 1926 that there could be no objection to the use of welded bonds "if applied to the head of the rail, and within the limits of the splice bar." Since that date there has been an increasing use of this type of bond for all purposes. Fig. 13 shows various forms of this type of bond. It has the advantage of low material cost and low installation cost. Being short and applied next to the end of the rail, it affords greater protection against broken rails than does a long bond placed around the splice bar. It is entirely exposed, which makes it easily inspected, although its exposed position makes it liable to damage from derailments and malicious interference, and to theft. There is, however, small value in the amount which can be stolen, because of its short length. On account of its short length, heating caused by heavy currents is rapidly dissipated by convection through the larger mass of terminal and rail metal, which allows use of other and less valuable metal than copper, to give, in some cases, a longer life under severe vibration, and to reduce the risk of theft.

It has been found that a coating of heavy grease has a tendency to prolong the life of these bonds under vibration, as well as to render them less attractive to theft and malicious damage.

Other Types and Methods of Bonding

Numerous other types and designs of rail bonds have been proposed, involving splice bar design and material, set screws, springs, etc., most of which have not been commercially successful for obvious reasons. Abroad, bonds of various types between one rail and the splice bar and from the splice bar to the other rail have been used to some extent. It is, however, obvious that this not only doubles the number of bonds and contact resistance points, but for the same number of contacts per joint has but a small fraction of the reliability for signal circuits that double or multiple bonding has. This method has, however, the advantage of getting the bond away from the point of greatest rail movement. No information is available as to the increased life of bonds applied in this manner.

Substitutes for Bonding

A discussion of the various methods of rail bonding would not be complete without at least a brief mention of various methods which have been tried to do away with their use.

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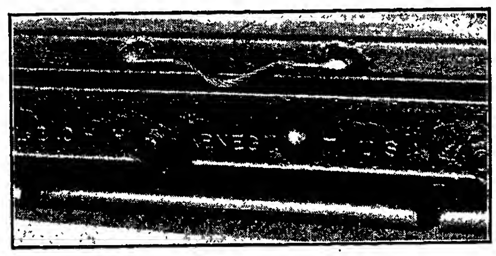

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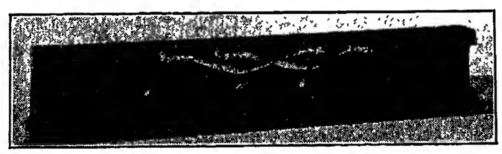

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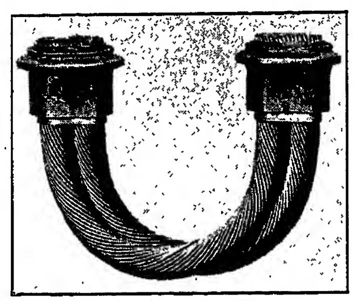

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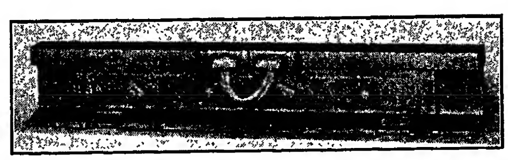

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Fig. 13—Flame weld Bonds

a. Stranded copper flame weld signal bond (one terminal not welded to rail)
b. Stranded steel flame weld signal bond
c. Double 250,000 cm. stranded copper flame weld bond
d. U-shape double flame weld bond—detail
e. U-shape flame weld bond on rail joint

One of the earliest attempts which was used with some success was to clean the inside of the angle bar and rail, and apply a small button shaped spring containing a soft amalgam which maintained the necessary contact between the two parts. Two such contacts were required per joint, one between each rail and the splice bar, being held in place by the splice bolts.

Some experiments have been made more recently both abroad and in this country with the process whereby a corrosion-resisting metal is sprayed in a molten state on the inside surface of the angle bar, and the adjacent surface of the rail. No definite information is available as to the efficacy of this method of joint treatment as compared with bonding, its prime object being originally to retard corrosion in the joint itself, which is considered a major cause for joints becoming loose. The present cost of this method of surface treatment makes it prohibitive in this country as compared with other methods of bonding.

On at least one section of steam railroad in this country operating electrically, no bonding whatever is installed, the integrity of the return circuit being maintained by careful attention to insure that the angle bar bolts are always kept tight, and by frequent connections between the rails and an aerial ground wire.

Welding the rails to the splice bars by various methods, and welding the ends of the rails to each other by the "Thermit" process, have been successfully used by the electric street railways to make better rail joints and to eliminate bonding. Where the rail is confined by pavement, these methods have produced excellent results, but on account of limiting opportunity for expansion of rail they have not been used on open track to any extent, except for third rail joints in one or two test installations. It is obvious that the stresses due to temperature changes in long lengths of rail connected in such manner might easily cause considerable trouble.

Several electrified railroads abroad are being operated without the use of any kind of electrical connection at the rail joints other than the splice bars themselves, the continuity of the return circuit being entirely dependent upon the tightness of these joints. In certain cases, the splice bars are specially designed to support the rail at points, instead of by linear or by surface contact, and these points are supposed to be kept bright and in condition for good electrical contact by the motion of the joint under the loads. No specific information is available as to the performance of such joints.

Concealed *vs.* Exposed Bonding

All bonds are necessarily located at the one place in the track which requires the maximum maintenance attention, namely, the rail joint. Consequently, exposed bonds are always more or less in the way when any work is done on the joint and are subject to damage from wrenches and other track tools. When applied to the rail head, they may be injured by derailments or dragging equipment. They are also exposed to malicious damage and to theft.

Against these disadvantages, the ease of application without disturbing existing joint conditions, and the ease of inspection, are important advantages.

Concealed bonds, (see Figs. 6, 9, 19) while free from the above mentioned hazards of damage and theft, may be carelessly installed and pinched when the splice bar is re-applied, (unless they are inserted behind the bar and later soldered) and if not damaged when the bolts are first tightened, may under such conditions fail shortly after from the movement of the joint. Such conditions are not apparent until a signal failure or test of the joint indicates the faulty condition, and the splice bar must be removed to discover and remedy the trouble. Joint testing, rather than mere visual inspection, is necessary to determine the condition of the bond.

When properly applied, however, the concealed bond on well maintained track has given a very excellent performance record.

Single *vs.* Double Bonding

As stated above, nearly all types of signal bonds are usually installed in pairs to assure the integrity of the track circuit. When traction current densities require bonding to the approximate equivalent capacity of the rail, single copper conductors might be too large for convenient application, so that usually two or more bonds having total conductivity requirements are applied to each joint, giving a multiple path for the propulsion current and likewise affording to signal circuits, if they exist, the required degree of reliability.

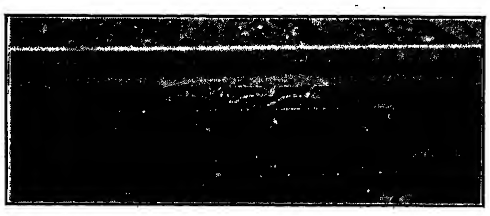


Fig. 14—Double Flame Weld Bond used on the New Haven Since 1928

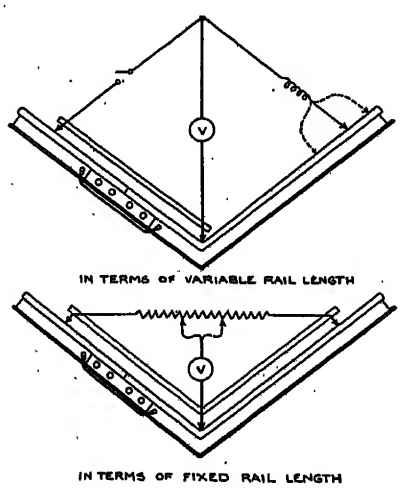
With the high-voltage systems of electric traction, the necessity for large bonds, or for more than one bond per joint, is not so great, especially if track signal circuits are not involved (as on some branch lines) unless the service is unusually heavy. Single bonding has given very satisfactory performance under such conditions. Where signal circuits are involved, the reliability is increased by using double bonds, which may be then of smaller cross section, and in some cases, no larger than a bond designed primarily for signal circuits. (Figs. 1, 4, 13c, and 14 show typical methods of double bonding.)

Bond Testing Methods

Many commercial methods have been devised for testing the electrical resistance of rail bonds in place, and thus determining their efficacy as part of the return circuit.

The method generally used is to measure, by the Wheatstone bridge method, the drop in voltage across the joint as compared with a fixed length (usually three feet) of the rail with a variable resistance; or with a fixed resistance and a variable length of rail; and there are several instruments on the market, portable in form, for making tests of this kind (see Figs. 15A and B). It is obvious that there must be a direct current flowing in the rail, to enable a test to be made.

On d-c. railways there is usually enough current flowing in the rail to give proper indication on the instrument, although where traffic is infrequent such current may not exist. For such conditions a small dry battery is often used with the testing apparatus, or a definite amount of current may be drawn from the contact conductor, through suitable resistance, to furnish the required rail current.



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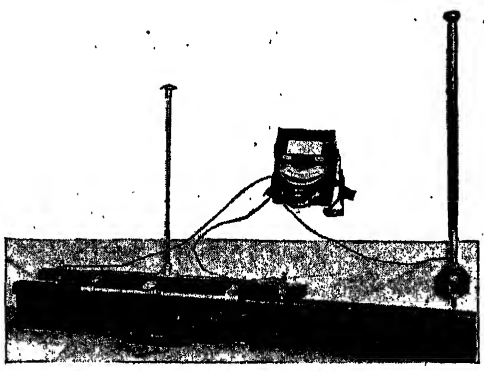


b

FIG. 15

a. Bridge methods of bond testing
b. Portable bond testing instrument—bridge method, giving joint resistance in equivalent length of rail

Some electric roads have fitted up special cars with more elaborate equipment, which not only indicates but also records, and marks with paint, faulty bonds in the track over which the car is operated.

On the "New Haven," which is operated by alternating current, a portable testing set, shown diagrammatically in Fig. 16, is used. This consists of a storage battery B which delivers a definite amount of current (50 amperes), adjusted by means of a variable resistance R, and measured on a millivoltmeter in conjunction with the shunt S, when the three-pole double-throw knife switch $S\ W$ is in the correct position. With the knife switch in the other position, the millivoltmeter $M\ V$ reads directly the drop across the bonded joint.

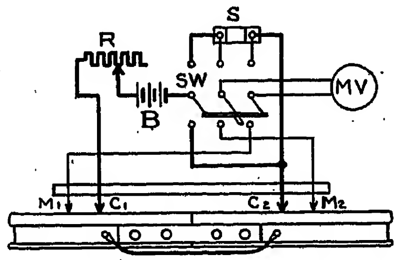


FIG. 16—PORTABLE BOND TESTING SET USING POTENTIAL DROP METHOD

An upper limit reading on the millivoltmeter is established for a bond known to be good, and all joints which test higher are marked for replacement. The Boston & Maine also uses a similar testing set.

No commercial method of testing yet devised will give other than an approximate indication of actual resistance conditions between the bond and the rail, since such testing is invariably done with the splice bar in place and in many cases, especially where there is no necessity to bond to the full capacity of the rail, a tight joint unbonded with the splice bars in good condition will test lower than will a properly applied bond without splice bars. The real test for satisfactory electrical contact is from the bond conductor near its terminal, to the rail to which the terminal is attached, but such tests obviously cannot be made on all types of bonds, especially where they are entirely concealed.

II. EXPERIENCE WITH RAIL BONDING ON ELECTRIFIED STEAM RAILROADS

New York, New Haven & Hartford Railroad. The history of traction rail bond application on the New Haven, going back as it does to the earliest days of electric operation of railroads, may be cited somewhat in detail as indicative of the development of the art in general. In the earliest installations beginning in 1895, where the overhead contact or the third rail was employed at 600 volts direct current, the flanges of both the third rail and the traction rails were drilled directly under the joints and a short heavy laminated copper bond was used with split stud terminals expanded into these holes by means of small metal wedges, (see Fig. 17). Later, in 1900, when several additional branch lines were equipped for electric operation at 600 volts direct current, with overhead contact conductor, the track rails (mostly 75 to 90 lb. weight) were bonded with two compressed terminal bonds consisting of 4/0 stranded copper wires around each joint attached to the

web of the rail. No attempt was made at that time to conceal or protect these bonds. The service on these electrified branch lines consisted of electric passenger trains composed of from one to six 40-ton cars, on half hourly schedule, with one or two steam freight trains, daily. The tracks had ordinary earth ballast and consisted of rails weighing from 75 to 90 lb., with standard 4-bolt splice bars. This type of bond proved

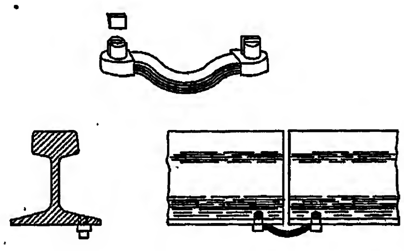


FIG. 17—EARLY BOND ON THE NEW HAVEN (1895)

very satisfactory both electrically and mechanically, although where joints became loose some breakage of the wires near the terminal occurred after two or three years of operation; and in the urban districts there was some loss due to theft.

Based on this experience, it was but natural, when the electrification of the main line between New York and Stamford was undertaken in 1906, with 11,000 volts 25 cycle alternating current, that a bond of this type should be adopted for the rail return. One 4/0 compressed terminal stranded copper bond was accordingly installed around each rail joint (see Fig. 5). No record was kept of the performance of these earliest bonds on the first electrified section of the main line. The track was well ballasted with broken stone. The rails were 100 lb., but not new, and the joints were with 4-bolt angle bars. The traffic consisted of frequent high-speed passenger trains and heavy freight service, with axle loadings up to 60,000 lb. It is known that some failures were experienced due to broken strands near the bond

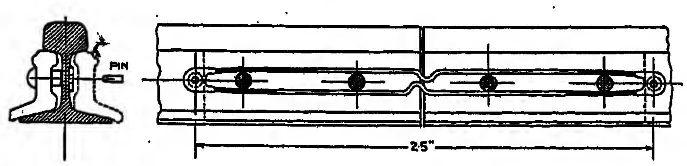
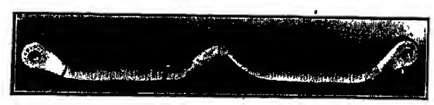


FIG. 18—No. 0 DUPLEX PIN EXPANDED STUD TERMINAL BOND USED ON THE NEW HAVEN

terminals, and some loss due to theft occurred in the more densely populated districts.

Several years' experience on this section of the main line demonstrated that with such a multi-track construction. frequently cross-bonded, the rail currents with the high-voltage system used were not of large magnitude, and therefore smaller bonds could be used. The pin expanded terminal bond had already come into extensive use so that in 1911, when the 6-track Harlem River Branch was electrified, a No. 0 duplex pin expanded terminal bond (see Fig. 18) was used on the main track rails, applied beneath the splice bar for protection against mechanical injury and theft. The duplex type bond was selected as affording a double conductor for maintaining signal circuits in event one conductor should become broken. In the several very large freight yards on this branch line one rail only was bonded in each track and for this purpose a No. 2 copper-covered steel wire was used, located under the splice bar where the space permitted, otherwise around it, attached to the rail by means of channel pins.

In 1913 when the main line to New Haven was electrically equipped, the same type of No. 0 duplex bond with pin expanded terminals was used on the main tracks. This type of bond was continued as standard for several years, during which period the failures experienced were carefully studied. One of the principal causes of failure was found to be the faulty application of the splice bar after the bond had been applied, causing the bond strands to become pinched, and after a short time, broken. About 1923 an extensive rail renewal in



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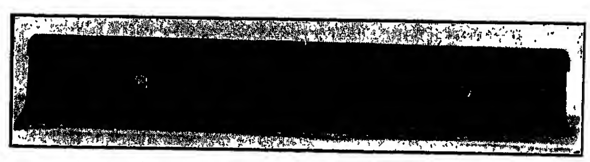

b

FIG. 19

a. Concealed pin expanded stud terminal bond No. 0 stranded copper, single conductor used on the New Haven, 1923-1928
b. Bond in place in rail joint

this section brought about further study of this problem, with the result that the standards were changed to a single conductor bond, of the same capacity (No. 0) also with pin expanded terminals, (as shown in Fig. 19 A and B) concealed under the splice bar.

On the single track branch line between Stamford and New Canaan which is 7 miles long and fed from one end, a 4/0 single conductor bond with pin expanded terminals, exposed outside the splice bar, was adopted, since the conductivity requirements were somewhat greater than on the main line. The latest major installation of pin expanded terminal bonds was made in 1925, when the Danbury Branch was electrified. A 2/0 single conductor pin expanded terminal bond was installed beneath the splice bars on this section, which is single track, fed from balancer transformers at each end and an intermediate point. Single bonds at each joint of both rails were deemed adequate on both these branch lines which have in general no track signal circuits.

On the busy yard tracks, the original single No. 2 solid copper-covered steel bond soon proved inadequate mechanically and was replaced about 1914 with a single No. 3 stranded copper conductor pin expanded terminal bond. Some of these bonds are still in service, although as a type, they soon gave evidence of being inadequate mechanically. For the last 8 or 10 years the practise has been to bond one rail of each yard track and side-track with one No. 0 single copper conductor, exposed pin expanded terminal bond, which has given satisfactory performance for this type of track and service conditions. (See Fig. 20.)

Failures of the pin expanded terminal type of bonds

Fig. 20—Exposed Pin-Expanded Stud Terminal Bond used on Yard Tracks on the New Haven

on main tracks have been due chiefly to mechanical fatigue, from vibration, which causes the bond to fail near its terminal; or due to pinching (in the case of concealed bonds) which has caused a similar failure near the center of the bond. These failures have been estimated to be at the rate of 0.25 per cent per year.

During the period 1920-1926 the flame-weld bond had been developed and had gained extensive use, so that in 1926 when the New York Connecting Railroad was electrified, as an extension of the New Haven's electrified territory, it was felt that this type of bond would be justified for economic reasons. Each joint was accordingly bonded with one 13 in. No. 0 stranded copper bond having forged copper terminals, flame-welded to the outside of the head of the rail. These bonds failed almost completely within one year after their application, due to strand wires breaking near the terminal from vibration. This particular track was about nine years old and had 125 lb. rail with standard 4-bolt angle bar joints and broken stone ballast. The natural period of vibration of the particular length and size of bond used was held to be responsible for the large number of failures, and further experiments were made using a smaller shorter bond, and installing two per joint, since signal track circuits were also involved. These gave very much better results, and finally resulted in the adoption, as a standard, of a No. 2 stranded copper bond, 7½ in. long, with pressed steel terminals, using two bonds per joint, (see Fig. 14).

This type of bond has been used since 1928 on all new rail laid in the electrified territory and as the program calls for practically complete substitution of 130-lb. rail for the present 107-lb. rail within the next year or so, it will not be long before this type of bond has replaced the pin expanded type for main track use.

Failures of this type of bond are readily found by the track inspectors and taken care of first with a temporary bond clamped to the rail flange around the joints, and later replaced in kind. The failures experienced have been mainly the breaking away of the terminal from the rail, due to faulty weld or application too near the top of the rail, or the breaking of the strands at the terminal due to vibration. Occasionally strands break inside the terminal and remain in place. Such failures may be found by testing the bond mechanically with a slight prying force. These bonds are given a coating of a special grease after they are applied, which not only tends to damp the vibration, but prevents corrosion of the terminals and wear of the strands and also renders them unattractive to malicious interference.

All bonds are tested twice annually by means of a portable testing set already described. (See Fig. 17.)

On the New Haven, the track supervisors are respon-

a

b

Fig. 21

a. Double flame weld bond used on the Baltimore & Ohio, Staten Island lines

b. Installing flame weld bonds on the B. & O., Staten Island lines

sible for the bonding, reporting to the division engineer. The maintenance organization consists of one bonding foreman, three assistant foremen, and 24 bonders. There are approximately 382 miles of bonded main track, and 195 miles of bonded track in yards and sidings in the a-c. electrified zone.

Baltimore & Ohio Railroad. Pin-expanded stud terminal bonds have been used, one per joint, until very recently on the 650 volt d-c. Belt Line electrification in Baltimore, and have given very satisfactory service. On account of the frequent rail renewals due to heavy volume of traffic, the life of the bonds was relatively

short. On the latest rail renewals in the longest tunnel (1.25 miles) two flame-weld bonds were applied to the head of the new rail at each joint and their performance to date has been very satisfactory. The pin terminal type has indicated an increase in resistance as the period of service has lengthened, due to corrosion of the rail contact surface, sufficiently to cause unbalancing of track signal circuits, and necessitating numerous renewals for this reason.

The Staten Island lines of the B. & O., also operated at 650 volts direct current, when electrified in 1926 were equipped with new 100-lb. rail, and flame-weld bonds were used, two applied to the outside of the head of the rail at each joint (see Fig. 21-A and B). No injurious effect on the rail has been indicated caused by welding, and no bonds have been lost to date (except on one or two sharp curves due to extreme wear of the inside rail), indicating a very satisfactory performance. The principal data on both these installations are given in Table I.

TABLE I

	Belt Line electrification		Staten Island electrification
Weight of rail	130 lb. R. E.		100 lb. A. R. A.
Type of joint	100% Hd. contact, reinforced		100% Hd. contact
No. trains per day (One direction)			
Passenger	17		233
Freight	20		4
Axle loads max.	60,500 lb.		32,440 lb.
Type of bond	Pin exp. terminal,	flame weld	Steel terminal, flame weld
No. bonds per joint	1	2	2
Size of bond	400,000 cir. mils	250,000 cir. mils	250,000 cir. mils
Length of bond	42 in.	13½ in.	13½ in.
No. of strands	91	91	91
Cost of bonds	$2.12	$0.58 each	$0.58 each
Cost of bond application per joint	$4.32		$3.45
Percentage of renewals per year other than for new rail	4%	—	—

Boston & Maine Railroad. Initial installation in 1911, for the 11,000-volt a-c. electrification of the Hoosac Tunnel, was with 4/0 stranded copper, compressed terminal, exposed bonds, one per joint of both rails, applied to web of rails outside the angle bar.

During the early years of operation, renewals were made using 4/0 pin expanded terminal concealed duplex bonds, applied to the web of the rail under the splice bar. In 1925 the short U-type of flame-weld bond was adopted, of 4/0 capacity, 7 in. long, similar to bond shown in Fig. 24, applied to the outside head of the rail, and this type has been continued since as standard. Fig. 22 shows installation equipment and crew.

During the past twelve years bonds have been tested at intervals by passing a direct current from a portable storage battery or generator through each joint and reading drop across joint with a millivoltmeter. The condemning limit for the bond is set at 7 millivolts with a current value of 60 amperes.

No definite record of failures has been kept, but performance seems to indicate a life of approximately 7 years for the pin terminal bonds under existing conditions. Failures of flame-weld bonds have been due chiefly to improper welding, and occasional shearing off

FIG. 22—FLAME WELD BONDING EQUIPMENT USED ON THE BOSTON & MAINE

of the bond. The track is 100-lb. rail with 100 per cent angle bar joints.

Chicago, Milwaukee, St. Paul & Pacific Railroad. The initial installation of bonds in 1914 and 1915 for

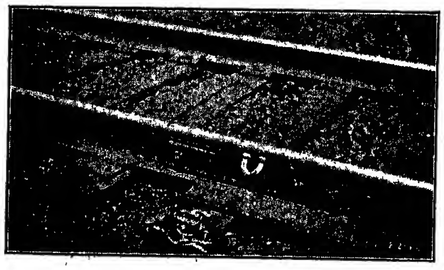

FIG. 23—U-SHAPED FLAME WELD BOND ON THE DELAWARE, LACKAWANNA & WESTERN

this 3000-volt d-c. electrification was with 250,000-cir. mil single conductor pin expanded terminal bonds, one or two per joint of both rails, depending upon propulsion current requirements. Where the joint construction

FIG. 24—U-SHAPED FLAME WELD BOND ON THE B. & M., C. M. St. P. & P., AND ILLINOIS CENTRAL

and conditions permitted removal of splice bar, concealed bonds were used. If space under the angle bar permitted, but conditions did not allow of removing the bar, concealed bonds were used with one detached terminal, soldered on the bond strand after bond was in

place. Where joint construction did not permit the use of concealed bonds, exposed bonds were used around the splice bar, on the inside of the rail, as this location appeared to result in less damage to the bonds in cases of derailment. The length of these bonds varied from 20 in. in the case of concealed bonds, to 37 in. and 42 in. in the case where two bonds of the exposed type were used at each joint.

On account of the high value of the bonds, they were, when removed from the rail for any reason, brought into the store-room, re-formed, and the terminals re-shaped, and returned to stock.

In 1921 the use of flame-weld bonds was started, since which time they have been used on all new rail, and for much of the maintenance work since 1924. One U-shape double conductor bond, 7 in. in length, of 4/0 capacity, and having pressed steel terminals, is used, welded to the outside of the head of the rail (see Fig. 24). This type of bond was adopted because of its lower cost, more reliable and permanent contact with the rail, and greater ease of inspection as compared with the original pin terminal bonds. The estimated relative economy of the two types is as follows:

Pin terminal type	37 in.	Material $1.50	Labor $0.45	Total $1.95
Flame welded type		Material 0.70	Labor 0.38	Total 1.08

showing a saving of $0.87 per joint, which is increased in territory where double bonding was formerly used, since one welded bond only is used in these locations. Experience to date indicates a very satisfactory performance of this type of bond. Many of the old pin terminal type originally installed are also still giving satisfactory service.

Delaware, Lackawanna & Western Railroad. For this 3000-volt d-c. electrification, construction of which is nearing completion, the engineers have selected after careful tests under actual track conditions, a 4/0 U-shaped double stranded conductor bond, 8½ in. long, with steel terminals (see Fig. 23), which will be welded to the outside of the head of the rail at the joint, using one bond per joint where both rails are used for the propulsion current return, or two per joint where single rail return is used. This type of bond was selected because of lower first cost and lower resistance as compared with longer pin terminal type bonds.

Illinois Central Railroad—Chicago Terminal Electrification. Flame-welded bonds are used on the Chicago Terminal electrification which has 133 miles of main track and 17 miles of yard track operated at 1500 volts direct current. Both rails are used for track signal circuits and for traction current return and joints are single bonded except through interlocking plants, where one rail only is used for traction return with joints double bonded, the other rail being single bonded with the same type bond for signal track circuit.

The rail used is standard ARA-A section 9020, joined with standard I. C. 24-in. oil treated angle bars, having four 1-in. bolts and with tie under each end of angle bars. The traffic is very dense, consisting chiefly of suburban passenger service. The speed of all I. C. trains averages 26.4 miles per hour and the average train-miles per day is 7306, with 27,366 car-miles per day. The cars average 63.4 tons each with load and have 4 axles. In addition to the I. C. trains, the Chicago, South Shore & South Bend operate their electric suburban service over part of the terminal tracks, averaging 1169 train-miles or 2934 car-miles daily. The average car weight of this service is 57.1 tons, carried on 4 axles.

A single 4/0 -127 strand bond about 8 in. long, with solid copper sleeve terminals, was originally installed. The terminals were welded to the outside head of the rail, approximately 7 in. between terminals, thus leaving enough slack in the bond for a slight bend or depression to allow for expansion and vibration. Bonds were coated with heavy crude oil at the time of installation. After a three year period of operation, it was felt that a change was desirable because of malicious interference, a large number being damaged in certain areas by trespassers turning the bonds up over the rail and allowing trains to cut them off. It was therefore

Fig. 25—Single Flame Weld Bond used on the Reading

decided to discontinue the use of this bond and to make all replacements with a standard U-shaped bond.

The U-shaped bond now used consists of two No. 0, 61 strand copper conductors 8 in. long, fitted with thin copper sleeves at each end, clamped into a pressed steel terminal which is flame welded to the outside of the head of the rail (see Fig. 24). Some of these bonds have now been in service for three years and are proving in general very satisfactory, although there are certain features which have given some trouble. The core of the stranded conductors seems to be under a greater tension than the outer strands, since the terminals are clamped on before the strands are bent into the U-shape, and the center strands invariably break first under fatigue due to vibration. Vibration also causes the strands to wear away where the two conductors cross each other, and it has been necessary to renew some bonds on this account. Coating the bonds with a heavy oil seems to overcome this feature, and in addition, tends to damp the higher frequency vibrations, thus prolonging the life of the bonds in general. This treatment also retards corrosion and oxidation of the bond and its terminals.

About 49,000 bonds were installed originally. Of these, approximately 19.39 per cent have been replaced by U-bonds due to all causes. During the three and one-half year period of operation, 19,286 U-bonds have been used, and of this number a total of 9.88 per cent have been replaced. The following tabulation indicates the approximate proportion of bonds replaced, and the chief causes for their replacement:

	Original Bonds	U-Bonds
Rail changes	11.85%	8.03%
Fatigue failures from vibration	3.01	0.43
Malicious interference	2.32	..
Defective welding	1.36	0.40
Dragging equipment	0.85	1.02
Total replacements	19.39%	9.88%

About 90 per cent of the bonds removed for rail changes can be reclaimed and used again. It is expected that fatigue failures may increase as the service life lengthens. Malicious interference losses were chiefly due to trespassers turning up the original bonds on to the top of the rail. The U-bond has eliminated this item. Defective welding includes original application and re-application if removed for building up joints by the welding process, the latter operation being the chief cause for failures of this type.

The traction bonding maintenance is in direct charge of an Assistant Engineer reporting to the Supervisor of Electrical Maintenance. Under him are three welders and three welder's helpers. The bonded area is divided into three districts with one welder and one helper responsible for each district. A fourth welder is employed as an instructor and to assist otherwise.

New York Central Railroad. The New York Central has for many years standardized on a pin expanded stud terminal duplex bond, entirely concealed beneath the splice bars, for the 660-volt d-c. electrification of the New York Terminal, which includes 328 miles of bonded track. Bonds of 400,000 cir. mils or 500,000 cir. mils capacity are used, two per joint on both rails. This bond is shown in Fig. 9. The terminal studs are 1 in. in diameter, spaced 16.8 in. apart. The rail used is 105 pound Dudley section, connected at the joints by six-bolt angle-bars, with a tie immediately under the ends of the rails. The service is unusually severe, 505 passenger trains and 45 freight trains operating over the electrified territory daily. Axle loadings are as high as 50,400 lb. on the heaviest locomotives, the average being about 38,000 lb.

Each joint is tested at regular intervals, the whole bonded area being covered about twice in three years.

Norfolk & Western Railway. On the section of the Norfolk & Western, which is electrified with 11,000 volts alternating current, a No. 0 concealed, stranded, pin-expanded stud terminal bond similar to Fig. 10A has been used since inauguration of electric operation.

Originally, the bonds had one pin-expanded terminal forged on, and the other end was soldered into a separate expanded pin terminal after being fished under the splice bar. This practise of having one terminal forged on has since been discontinued, to avoid having two different terminals, and because the forged-on terminal cannot be re-applied if the bond wires are damaged. Two separable terminals are now used, one soldered to each end of the bond strand, which simplifies maintenance stock and permits making bonds to any length required. These soldered terminals have not given any more trouble than the forged-on terminals which they replaced. No definite records have been kept of the bond maintenance cost, few bond failures occurring before they are removed on account of changing rail.

The terminals, after removal, are re-shaped and used again where possible, using an oversize pin.

The track is laid with 130-lb. rail with continuous joints. The traffic consists chiefly of very heavy tonnage trains with high axle loads at low speeds. Rail life is so short that broken bonds are practically unknown.

The type of bond used has been very satisfactory because of its ease of application without special heavy tools difficult to transport, since bonders are sent out considerable distances from headquarters to install bonds as rails are changed; also on account of the ability to salvage the terminals and to re-apply them.

Pennsylvania Railroad. Experience with electric traction rail bonds has been obtained by the Pennsylvania Railroad System in four zones, namely, the West Jersey & Seashore Railroad, the Long Island Railroad, the New York Terminal electrification, and the Philadelphia suburban electrification.

The West Jersey & Seashore Railroad line between Camden, Millville, and Atlantic City, New Jersey, makes use of a 650-volt d-c. third rail system. Multiple unit trains with maximum axle loadings of 31,000 lb. are operated at maximum speeds of 70 mi. per hour. Local steam freight service is also operated over the electrified lines. These lines can be roughly classed in the medium traffic zone, with cinder and stone ballast, and rail weights of 100 lb. and 130 lb. P. S. section.

The original traction bond used was a compressed terminal concealed bond of 400,000 cir. mils cross-section. These bonds showed a tendency to fail under the joint bars of the joint due to a pinching action between the bars and the flange of the rail. Due to the difficulty of detecting these failures and to the difficulty of making a replacement, this type was abandoned and an exposed compressed terminal bond 35 in. long of 400,000-cir. mils cross-section substituted. This bond was satisfactory from the point of view of ease of maintenance and length of life. Because of the relatively large amount of copper in the bond some difficulty has been experienced due to theft. The cost of this bond installed is high as compared to more recent types of bonds, and investigations are being carried out to determine a cheaper bond suitable for the service conditions imposed.

Since the initial electrification in 1906 with the d-c.

650-volt third rail system, traction rail bonds have been installed on the Long Island Railroad under a variety of service conditions, ranging from dense main line multiple unit and freight and passenger steam traffic to light branch line service with maximum speeds up to 70 mi. per hour. Rail weights have varied from 70 lb. A. S. C. E. to 130 lb. P. S. section, and axle loadings from 15,500 lb. to 33,200 lb. for multiple unit cars and from 8000 lb. for empty freight cars to 75,000 lb. for electric locomotives. Roadbed conditions have generally been good with cinder ballast predominating.

A soldered type of rail bond was adopted for the initial electrification in 1906. These were short bonds soldered either to the ends of the joint bars and to the head of the rail, or to the under side of the web at the rail ends. These developed failures at once under rail vibration, the soldered terminal breaking away from the rail.

A concealed compressed terminal bond was then used. This was a double cable bond so formed that it would fit around the joint bolts under the joint bars. These developed broken strand failures under the joint bars, due to vibration and to a pinching action between the bars and the web of the rail.

A long semi-concealed single cable compressed terminal bond was then developed. Because of its length, the copper cross-section had to be increased in order not to increase the joint resistance. While the service life was favorable in length, the cost of the bond was disproportionately high and maintenance was relatively difficult. Typical failures were similar to those of the double cable bond.

Development of a brazed terminal bond was then begun (1912). This was first a U-shaped ribbon bond. Difficulty was encountered in applying this due to a new design of joint bar with a projecting shoulder under the head of the rail. This was especially difficult where two bonds per joint were required. Broken ribbons also developed under joint vibration. Several adaptions of this U-ribbon bond were tried without successfully overcoming its objectionable features.

The present type of rail bond was then developed. This is a 250,000-cir. mil single cable bond 13 in. long with a terminal brazed to the head of the rail (see Fig. 4). There is only a slight loop in the bond, sufficient to provide for rail movement. This type has worked out quite successfully under the traffic and roadbed conditions generally prevailing on the Long Island Railroad. In general the life of the bond equals that of the rail, except at those points where a considerable amount of joint vibration exists. The majority of failures there are due to broken strands in the bond.

The New York Terminal electrification also uses the d-c. 650-volt third rail system. Traffic conditions are those of dense main line passenger service with axle loadings varying from 15,500 lb. for M. U. cars to 75,000 lb. for locomotives, and with maximum speeds of 70 mi. per hour. Roadbed conditions are exceptionally good, having rock ballast in general, with 130 lb. P.S. section rail.

A 35-in. exposed compressed terminal bond of 400,000 cir. mils cross-section was originally installed and has given very satisfactory service, the life of the bond generally equaling that of the rail. However, because of its relatively high cost as compared with recent types of bonds, its use has been discontinued and the standard Long Island Railroad bond (Fig. 4) is now being used for necessary renewals.

The Philadelphia suburban electrification uses the 11,000-volt single-phase overhead catenary contact system, requiring a traction rail bond of small cross-section as compared to the d-c. traction bonds. Service conditions are those imposed by heavy high-speed trunk line service on 100 lb. and 130 lb. P. S. section rail with rock ballasted roadbed, and with axle loadings varying from 8000 lb. for empty freight cars, and 37,000 lb. maximum for multiple unit cars, to 75,000 lb. for locomotives, and with maximum speeds of 70 mi. per hour.

The original traction rail bond used was a pin-expanded concealed bond with the cable of the bond soldered into the pin terminal which gave satisfactory service life. Typical failures of this bond were by broken strands under the joint bars of the joint. A flame-weld type of bond, No. 1 in cross-section, 7½ in. long, is now being used, the installed cost of which is approximately one-half that of the original type.

Favorable experience over an extended period of time with a taper pin terminal, double cable steel and copper strand exposed signal bond, supported by clips held by the joint bolts, especially with renewals made necessary by track maintenance, has suggested the possibility of still further reducing the installed cost of bonds for this service. Investigation shows that sufficient conductivity can be introduced in this bond in order to make it a suitable traction bond by the addition of nine copper strands to each cable and enlargement of the head of the cable, without changing the dimensions of the pin end of the terminal. The bond is thus interchangeable with existing signal bonds and experimental installations are now being made. (See Fig. 11B.)

It can be deduced, in general, from the Pennsylvania Railroad System experience with various types of bonds under differing service conditions that: (1) an exposed type of bond, so designed as not to interfere with track joint maintenance, is necessary; (2) all types of bonds so far used will fail on track so maintained as to permit a considerable amplitude of joint vibration; (3) the typical failure under such conditions is due to broken strands or ribbons near the bond terminal; (4) the installed cost of large section traction bonds for d-c. systems can be brought to the lowest point by using types that do not require drilling of the rail, as where the bond terminal is attached to the outside head of the rail by a welding or a brazing process.

Experimentation under actual service conditions is

now being carried out to determine those types most suitable, from the points of view of installed cost, life, and ease of replacement, for the various service conditions to be met. Sufficient experience has not yet been obtained to permit of definite conclusions.

Reading Railroad. The Reading, which is electrifying some of its suburban traffic routes in the vicinity of Philadelphia, with 11,000 volts alternating current, but which is not yet in operation, has conducted tests with a number of experimental installations of bonds to determine the most satisfactory type for the track and operating conditions met with.

The standard rail used for main line tracks is 130 lb. of the "head-free" type. With this type of rail the depth of the vertical section of the head is only about ¾ in., of which ⅜ in. must be allowed for wear. The full depth of wear must be allowed on outside of railhead as well as inside, since rails are canted and foreign cars with wheels worn by level rails wear the canted head-free rail particularly on the outside edge. There remains only about ⅜ in. of vertical section, which had to be given thorough consideration in preliminary consideration of types of bonds, so that the limitations of the welded bond might be determined. The remainder of the rail head slopes at an angle of 29 deg. from the vertical and there was some question as to whether this would be suitable for welding.

Test installations of welded bonds were made, largely for the purpose of determining any limitations in application of the bond. These included various sizes of bonds from 250,000 cir. mils to No. 2, the latter being a commonly used size of welded signal bond. It was determined definitely that there was no appreciable inconvenience in welding either a large or a small bond to the head-free rail and the sloping side of the rail head could be used readily for this purpose.

The test bonds are also being observed to note any effect of fatigue but the length of time available for such observation has not yet been sufficient to show any conclusive differences.

Conditions of traffic on this rail will include suburban passenger service, main line passenger traffic, and main line freight trains. The heaviest axle loading for both through passenger and freight engine is approximately 65,000 lb. and on some sections of the railroad the speed of passenger trains will regularly be 85 mi. per hour. Density of traffic will be as great as 3-minute headway on certain of the lower speed sections of the line. Freight traffic will include heavy tonnage coal trains traveling at relatively high speed.

The continuous head-free type joint is used with the 130-lb. rail and an unusually high standard of maintenance is obtained throughout all sections of the territory. Joints are therefore depended upon to be free from play, so that weaving of the bond need not be provided for. Observations also indicate that vibration conditions will not be severe even under the heavy conditions of traffic.

Theoretical comparison of short welded bonds and expanded pin terminal bonds extending beyond the limits of the angle bar, and having capacity to give comparable resistance of joint showed that the installed cost of the copper pin expanded terminal type of bond would be greatly in excess of the cost of a short bond welded to the head of rail. The latter, as is well known, also has some advantage in the case of broken rail protection. The pin expanded terminal type was eliminated from further consideration. The electrically welded bond was eliminated because gasoline engine driven generator sets would be required after operation as well as during construction, since trolley voltage will be 11,000 volts alternating current.

A detailed study of maximum current in the rails showed that a short welded bond as small as No. 1 gage would have ample current carrying capacity and that moreover the large amount of contact of the continuous joint bars with the high degree of maintenance would give further factor of safety as to carrying capacity. The problem therefore became one of mechanical requirements rather than electrical. Accordingly, a No. 1 A. W. G. 61 strand copper flame-weld bond, 8 in. long with 1½-in steel terminals has been adopted, one applied to each joint of both rails. (See Fig. 25.)

Observation of the various sizes of welded bonds applied for test indicate that long life can be expected from a small bond such as No. 1 as well as from a larger bond of 4/0 or 250,000 cir. mils capacity. (Study of test results on some of the other railroads verified this view.) Although the installed cost of the larger bonds is not higher in direct proportion to the size of bond, they will cost materially more and it is therefore considered that a small, short welded bond will be adequate as well as most economical. This bond will furthermore lie snugly within the limits of the angle bar and be well protected from damage by track wrenches. The U-type of bond is impracticable due to the shape of the angle bars, and the straight type of bond with a liberal amount of loop has been chosen. Consideration was given to using two bonds per joint, and it was decided that the advantages would be very small in comparison to the increased cost of installation and maintenance.

Branch lines will have 100 lb. R. E. rail but the type of bond chosen for the 130 lb. H. F. rail is equally suitable for the smaller rail section, and also for 130 lb. R. E. rail.

Virginian Railway. The Virginian operates probably the heaviest freight trains in the United States. The traffic is very similar to that of the Norfolk & Western, consisting of very heavy tonnage trains with high axle loads at low speeds. The greater part of the main line in the electrified territory is of 130-lb. rail, with 4-bolt, 26-in. continuous rail joints. Sidings and yard tracks are mostly of 100-lb. rail, with either 4-bolt or 6-bolt rail joints. Locomotive axle loads are as high as 79,000 lb. and loaded freight car axle loads are as high as 53,000. The freight traffic consisting chiefly of coal,

is handled eastbound from the mines to tidewater, with as many as 10 to 11 tonnage trains daily including local service. The westbound traffic consists of handling the empty cars back to the mines. The passenger traffic is light, with but three trains each way daily.

The main line, which is double track for 22 mi. and single track the remainder, has both rails double bonded at each joint with two No. 0 37 strand copper conductors of lengths varying from 32½ in. to 54 in., having pin expanded stud terminals ¾ in. in diameter by 13/16 in. long. (See Fig. 10B.) The hole through the terminal is 11/32 in. in diameter and is expanded with a 7/16-in. diameter steel pin. Double bonds are used throughout the electric zone because of the heavy currents involved in moving trains of from 6000 to 9000 tons over the heavy grades which exist on this line; also to afford protection to the joint if one bond should fail. Side tracks have both rails single bonded to the main track every 1000 feet.

Two forms of bonds were used, depending upon the nature of the rail and joint. Where space under the splice bar permitted, two semi-concealed bonds of the same length, with terminals extending beyond the angle bar were used, one on the inside and one on the outside of the rails. This type bond has a crimp or double bend between the first and second bolts to provide for expansion and flexibility; and to avoid the necessity of removing the splice bar it has only one forged-on terminal, the other end being soldered into a separate terminal after being fished underneath the splice bar. Where space under the splice bar was not sufficient, exposed bonds having forged-on terminals on both ends were used around the bar on the inside of the rail, long enough to provide the necessary working clearance, and to permit stapling to the ties. One bond is four inches longer than the other to avoid crossing. The location on the inside of the rail appeared to be more favorable to the bond in case of derailment.

Bonds are inspected and tested at regular intervals by means of a Wheatstone bridge type of instrument applied to each joint. Defective bonds are immediately replaced.

When rails are changed, bonds are knocked out, and reclaimed by careful inspection and re-shaping of terminals. When re-applied such bonds are expanded with an oversize pin ½ in. in diameter. After the second removal, the forged-on terminal is cut off, and replaced by a soldered-on terminal, giving the bond approximately its original length.

Experimental installations of other types of bonds have been made. One of such installations was the taper pin type similar to bonds used in signal service, of No. 0 capacity, applied to the outside of the rail around the joint, and held tight against excessive vibration and displacement by means of a clip under one of the track bolts. This type is satisfactory the first time it is applied, but cannot be satisfactorily applied the second time, as the taper terminal becomes loose in the hole in the rail.

The other experimental installation was of flame weld bonds, which so far have given satisfactory results. Failures of this type have been few, consisting of strands breaking out of the terminals. One case has been noted where such a bond became loose from the rail, probably because of improper welding.

SUMMARY

It will be seen that there is not only a great variety in the types of bonds now in commercial service, but that different performances may be expected under different conditions of operation or track maintenance from the same type of bond. It cannot be definitely said that any one type of bond requires a higher degree of track joint maintenance than another, although loose joints permitting of free movement of bolts and splice bars are, in general, destructive both to the short heat-applied types and the longer concealed types of bonds. It may be said that in general the greatest cause of mechanical failures in bonds is that due to fatigue, caused by vibration set up from the pounding of the heavy axle loads over the rail joints. It has been proved by laboratory and service tests that long bonds have a longer life than short bonds under the same conditions of such low-frequency vibrations. Hence it might be deduced that long bonds around joints would outlast short bonds applied to the extreme end of the rails. There are, however, under service conditions, vibrations of much higher frequencies, which are difficult to reproduce in laboratory tests. These vibrations can be, and often are, more destructive to the longer types of bonds than to the shorter types, under actual service conditions. The mass of the material involved, its physical properties, natural period of vibration, inertia, etc., all have a bearing on the problem and on the performance of any type under given conditions. All types of bonds seem to give satisfactory mechanical performance and length of service under good track joint maintenance.

Relative to electrical performance, the only cause for failure which is possible is the change in contact resistance, as between the bond terminal and the rail, or between the bond conductor and its terminal. The latter cannot exist without mechanical failure, in any properly manufactured bond; the former can exist without mechanical failure in the mechanically applied bonds only. The heat applied bonds thus seem to possess better characteristics from the electrical point of view.

The problem resolves into a careful study of all conditions which are to be met, and selecting the most economical type, taking into consideration the following requisites:

1. The bond must have a low resistance, in place.
2. Its contact with the rail must be permanent, so that resistance will not vary with time.

3. It must be easily installed by equipment readily available.
4. It must have a low first cost.
5. It must have a low maintenance cost.

Taking all factors into consideration the trend seems to indicate an increasing preference for the heat applied types.

ACKNOWLEDGMENT

Due acknowledgment is made to Messrs. J. H. Davis, Electrical Engineer of the Baltimore & Ohio, L. C. Winship, Electrical Engineer of the Boston & Maine, R. Beeuwkes, Electrical Engineer of the Chicago, Milwaukee, St. Paul & Pacific, H. M. Warren, Electrical Engineer of the Delaware, Lackawanna & Western, C. O. Beck, Assistant Engineer of the Illinois Central, H. A. Currie, Electrical Engineer of the New York Central, S. Withington, Electrical Engineer of the New York, New Haven & Hartford, R. P. Winton, Catenary Engineer of the Norfolk & Western, J. V. B. Duer, Electrical Engineer of the Pennsylvania, G. I. Wright, Engineer, Electric Traction of the Reading, and J .E., Sharpley, Electrical Engineer of the Virginian, for the original data and information concerning the practise and experience of these various roads, and to Messrs. H. H. Febrey of the American Steel & Wire Company, and D. H. Moore and W. P. Bovard of the Ohio Brass Company, for many of the illustrations.

Bibliography

(Partial)

"Modern Practise in Construction and Maintenance of Rail Joints and Bonds," Technologic Paper 62, U. S. Bureau of Standards, March, 1916.

"Bond Testing and Maintenance Practise," *Electric Ry. Jl.*, Jan. 17, 1925.

"Railbond Maintenance," (C. M. & St. P.), *Electric Ry. Jl.*, Feb. 20, 1926.

"Welded Signal Bonds on the Erie," *Ry. Signaling*, March, 1926.

"Welded Signal Bonds," *Ry. Rev.*, August 14, 1926.

American Railway Engineering Association, Report of Rail Committee, Vol. 28, March 1927.

Amer. Ry. Engg. Assn., *Proceedings*, Report of Committee on Electricity, Vol. 27, March 1926; Vol. 28, March 1927; Vol. 29, March, 1928; Vol. 30, March, 1929.

Amer. Elec. Ry. Engg. Assn., Report of Heavy Electric Traction Committee, *Proc.*, 1926, 1927, 1928 and 1929.

"Arcweld Rail Bonds," *General Elec. Rev.*, Sept., 1928.

"The Track Circuit Handbook," by M. W. Manz, 1927, (Ohio Brass Company).

"Electrification of Steam Railroads," by K. T. Healy, 1929.

Discussion

H. H. Febrey: This is the first time an attempt has been made to publish in one article the story of rail bonds on electrified steam railroads. It is rather surprising how much can be said about the art of rail bonding in all of its phases. Those of us who have been associated with the manufacture of bonds realize how much time and expense has been devoted to its problems for many years.

The manufacturers are devoting considerable attention to rail bonding problems in their laboratories. The company with which I am associated is extending laboratory facilities and equipment constantly and some very interesting and valuable facts are being determined from the numerous experiments which are being carried on. This will result in marked benefits to the consumer. It is natural that the development work is approached not only with the idea of improving the rail bond but to developing manufacturing processes which will reduce costs without any impairment of the quality of the bonds.

A glance at the manufacturers' catalogues today reveals an array of bond types which upon reflection seems unnecessary. Present welded type bonds require different designs of bond terminals for each welding method employed in their application. That is to say, we cannot interchange the rail bonds for application by oxy-acetylene flame, steel electrode arc welding, copper electrode arc welding and brazing or soldering. Because of this great variety of rail bonds and the number of sizes in which it is necessary to make them, the manufacturing practise has been very much of a hand proposition. Machinery used in manufacture is hand fed throughout the various manufacturing operations. Obviously this condition promotes high manufacturing costs. We may well say that bonds are "tailor made."

Efforts are being made to simplify bond designs and reduce the number of kinds, making them interchangeable between the different welding methods of application. We have been working for some period to develop machinery for automatically manufacturing rail bonds. Machines of this type are very expensive to develop and costly to manufacture. In order for them to be economical it is necessary to have a volume of work equal to the capacity of the machines. Simplification of bond designs will bring this about and the consumer will benefit to a very large degree if he will cooperate with the manufacturers in their efforts to reduce the number of bond designs to an absolute minimum.

In regard to the methods of applying welded bonds, there seems to be an unnecessary number of processes, all of which result in approximately the same cost per bond installed. Furthermore, the total resistance of the bonds installed is so nearly the same that we could very well eliminate some of the kinds of field welding.

Oxy-acetylene flame welding has many decided advantages for rail bonding, particularly on new work and for maintenance on high voltage systems where portable arc welding sets are not as practical to use. In arc welding we have three methods in use today; steel electrode, copper electrode and carbon electrode.

The simplest of these is steel electrode welding. It has the very decided advantage of being applicable by all types of arc welding equipment because the polarity of the electrode may be either positive or negative. The nature of the welding process is such that the same shapes of terminals which are correct for flame welding are equally suitable for steel electrode welding.

We are accustomed to demand the use of copper in welding the bonds to the rails, because it has lower resistance and is non-corrosive. Consequently we have the copper electrode and the carbon electrode methods of applying bonds with copper. Both of these methods require that the bond terminals be cup shaped or that a separate carbon mold be used with a more simple design of bond. The copper electrode process requires positive polarity of the electrode and demands a very much higher amperage than a steel electrode. The proper current requirements are actually beyond the range of a number of commercial welding sets which were designed primarily for steel electrode welding. The carbon electrode process requires negative polarity and therefore a rotary type of welder. If we could eliminate these welding processes the manufacturers' problems of design would be greatly simplified because the same bonds could be used for flame welding and steel electrode arc welding. The volume of bonds of one design would be increased and make economically possible the use of automatic machinery in production.

The use of steel for the terminals of welded type bonds has become largely standardized because better results are obtained

than with copper terminals. Steel is a rather poor conductor of heat and protects the bond conductor from the welding heat to a degree. In the mechanically attached terminal bonds where the welding is done directly upon the end of the conductor, those with steel terminals have stood up better under fatigue stress than similar bonds having copper terminals. If the poor heat conducting property of steel is carried further by welding a solid steel terminal to a copper conductor in the factory, still better results are obtained. A welded type bond is now being placed upon the market which has solid steel terminals welded on in the factory. The factory welding is accomplished in such a manner that the conductor is not injured by the heat nor injured mechanically. When this bond is applied the welding is done upon the solid steel terminal and the heat is not transmitted to the conductor nearly as much as with the mechanically attached steel terminal. In laboratory tests these solid steel terminal bonds have withstood vibration much longer than any bonds known before.

The solid steel terminal has slightly higher resistance but has the advantage of being applied equally well with the oxy-acetylene flame or steel electrode arc welding. The solid terminal simplifies the field welding and insures full efficiency of the bonds. The danger of the operator failing to weld all of the wires in the conductor is eliminated. This development follows the lines of simplification because the bond is applicable by two welding methods.

It is pertinent to emphasize the high cost of heat applied bonds as we have them today. In many cases too much is added to the price of the bond alone for accessory materials. The labor cannot be changed very much as the time of welding is quite rapid and approximately the same for the various processes in use. As an illustration, the Baltimore & Ohio Railroad reports a flameweld bond costing 58 cents for the bond and $1.73 installed, or $1.15 for labor and accessory materials. In other cases of flameweld bonding on electrification work we find the following relations·

Bonds	Labor and accessories
42 cents	62 cents
40 "	68 "
20 "	60 "
19 "	56 "

This is one of the problems which is being studied and experiments are being conducted in an effort to develop less expensive methods of installation, some of them contemplating a very marked reduction in labor costs.

Mr. Brown has pointed to failures of rail bonds from fatigue. Troubles of this nature have been more pronounced with the short welded bonds applied to the head of the rail than was the case with the more expensive concealed types of bonds or the long bonds installed outside of and around the splice bars. The fatigue failures are somewhat peculiar. Large numbers of bonds of the same type will stand up under the same traffic conditions and a certain percentage will fail very rapidly, sometimes in just a few months. Observation of the track and joint conditions does not seem to reveal why a failure occurred on one joint and not on another where the age of the rail and condition of ties and ballast are about the same. Considerable study has been given to the problem of vibration and almost countless vibration tests have been made by manufacturers on various kinds of machines which accelerate the failures of samples in order to break them within a reasonable length of time. Definite conclusions from these laboratory tests are almost impossible to reach. Consequently, efforts are being made to determine the nature of the vibration to which the bonds are being subjected and endeavor to reproduce similar conditions on the laboratory machine which will give an accelerated test.

Certain devices have been perfected for the study of vibration in all sorts of structures. One of these is known as the Electric Telemeter devised by Mr. O. S. Peters at the time he was with the U. S. Bureau of Standards. With this device an oscillograph record can be made of the vibration in any structure and the results are very enlightening. This device will be used on tracks under various traffic conditions and a study will be made in an effort to determine what takes place at rail joints where rapid failures of bonds occur. It may be of interest to point out that one record was made with the telemeter on one of our Eastern roads on 130-lb. rails with train speed about 70 miles per hour. The frequency of vibration was found to be as high as 1250 cycles per second. This high frequency vibration has a very marked effect upon the bonds and it is very probable that certain sizes and shapes of bonds respond to vibration corresponding with their natural periods and vibrate in harmonics of exceptionally high frequency.

It is hoped that an interesting insight of the vibration problem will be obtained with the telemeter. By applying these field observations to the laboratory vibration equipment we hope to obtain the correct frequency and amplitude of vibration which will enable us to accelerate failures in tests of all sizes and lengths of bonds. Up to the present time it has not been practical to test long bonds satisfactorily in the laboratory. Any frequency which has been selected for the laboratory equipment has been necessarily an arbitrary choice. Under these conditions we cannot be assured that the laboratory results are properly indicative of the manner in which the bonds will perform in service.

Mr. Brown in his paper mentions rather briefly the tapered pin terminal bond, Figure 11A and 11B. Experiments with different bonds of this general construction have given us information which is rather interesting. Until the tapered steel terminal bond was suggested for electric traction the experience with stud terminal bonds was confined entirely to copper terminals, either compressed or pin driven, that is, expanded with steel drifts. These copper terminals were of relatively large diameter, ¾ in. to 1 in. and sometimes 1-1/16 in. It was felt that the larger diameters were necessary for the larger capacity bonds. However, load tests on tapered steel terminal bonds have shown surprising results. In the case of the bond illustrated in Figure 11A and 11B, the total copper cross section is a little less than 1/0 AW gage. With a load of 400 amperes at 25 cycles the temperature rise in the conductor of a 48-in. bond is about 75 deg. cent. The ⅝-in. terminals remain cool.

While it may seem as though a backward step was being taken to consider long pin terminal bonds versus short welded bonds, the welded bonds are more expensive in first cost and more expensive to maintain. Comparing the installed cost of two No. 1 AWG 8½ in. flameweld bonds with one 48-in. double conductor bond mentioned in Mr. Brown's paper installed shows the latter to be but slightly over half the cost of the two flameweld bonds.

In the summary of his paper Mr. Brown points out certain requisites which have the aspect of the millenium in rail bonds. Items 1 and 2 combined with items 4 and 5 would result in perfect rail bonds. When all factors pertaining to railroad operation are taken into consideration should not the most economical bond be selected? We have developed new rail bonds which combine low first cost with low maintenance cost but which require some compromises in the other of Mr. Brown's requisites. In order to keep the maintenance cost down the bonds must stand up in service with minimum failures. Furthermore, it should be emphasized that many maintenance renewals are due to rail changes which occur regardless of the type of bond used.

G. H. Müller: The electric rail joint used by the Swiss Federal Railroads comprises a copper cable of 35 mm.² (0.54 sq. in.) cross section and 320 mm. (12.60 in.) long as indicated on the accompanying drawing.

The electric resistance of this type of rail joint is about 600 microhms, that of the electrically welded joint about 350

microhms and that of a joint without bond about 2000 microhms. In other words, since a rail length is usually 15 meters (16.40 yards) the conductivity is increased in the ratio of two to one by bonding the joints.

This considerable increase in conductivity naturally produces an important increase in the normal rail current.

The reduction in voltage induced in the conductors of a cable along the right of way when four rails are electrically bonded amounts to 46.6 per cent.

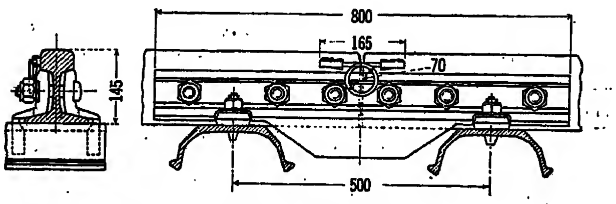

FIG. 1—SWISS FEDERAL RAILWAYS, RAIL JOINT

The ends of the copper cable are terminated in iron or copper blocks electrically welded to the head of the rail. Autogenous welding at the base of the rail has been abandoned because it caused numerous failures.

The results which have been obtained by electrically welded rail bonds have been very satisfactory.

Ivan Ofverholm: Rail bonds are no longer used in electrified railroads operated by the Swedish State. They were used in the beginning on the Ore railroad in the North of Sweden, but were discarded on account of high maintenance. The experience in Sweden has indicated that operation may be satisfactorily performed without rail bonds.

On some of the smaller direct current railroads in Sweden copper rail bonds are used. However, in no case are these railroads more than 15 kilometers long. The electrical engineers of these railroads would be glad to eliminate rail bonds but they have found it impossible when direct current is used.

The Swedish State Railways employ single phase distribution at 16,000 volts, 15 cycles per second.

M. Parodi: The system of electric traction for the French Railroads has been standardized on the basis of direct current at 1500 volts for use in France and at 3000 volts on the lines in North Africa. In the more remote colonies where local conditions are entirely different, a decision has not yet been reached between using direct current at 3000 volts and single phase at 11,000 22,000 volts.

The general characteristics of the French Railroads involve the handling of heavy currents, which necessitates the use of thoroughly reliable rail joints of low electrical resistance.

First Type. (Fig. 2) This rail bond consists of two copper cables of 180 sq. mm. (0.28 sq. in.) section and about 0.8 to 1

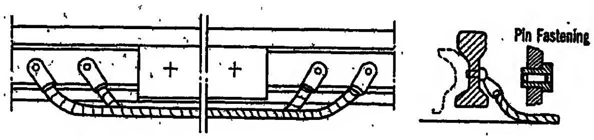

FIG. 2—TERMINAL CONNECTION BY MEANS OF PINS

meter (2.61 to 3.38 ft.) long, depending upon the type of rail. At each end of the cable is welded a copper terminal in the form of a cylindrical plug. The plug and its shoulder are drilled with a cylindrical hole. After the plug has been placed in a hole drilled in the web of the rail, a cylindrical steel pin tapered at one end with a maximum diameter of 18.5 mm. (0.73 in.) and a length equal to the thickness of the web of the rail, is forced into it.

The electrical resistance of the rail bond by itself (that is, with the splice bolts not tightened) is equivalent to that of a standard rail 3½ meters (11.5 ft.) long weighing 46 kg. per meter (92.7 lb. per yard). The electric resistance of the bond as installed (that is, with the splice bar bolts tightened) is equivalent to that of 1.85 meters (6.0 ft.) of standard rail.

The terminal is useless on the average after three re-installations; that is to say, this type of rail bond has a life covering three changes of rail.

The installation of this bond is simple, as it does not require skilled labor or cumbersome tools. It can be installed quickly and does not interfere with operation. On the other hand, the hole drilled in the web of the rail must be absolutely cylindrical, which is not easy.

After a time the steel pin corrodes, producing a reduction of pressure between the rail and the bond terminal. The passage of trains produces variations in compression on the rail; consequently, upon the terminal. The steel of the rail reacts to these variations of compression with more elasticity than does the copper of the terminal, and this may result in loosening. Loosening may be caused by the difference in coefficient of expansion of the two metals—copper and steel—which are in close contact.

These rail bonds are very liable to damage. They are sometimes broken by the track tools or by equipment dragging from trains. Furthermore, as the terminals are fastened at either end of the splice bars, the copper cable has considerable length, and as it lies on the ground, is in danger of being stolen.

This type of rail bond was adopted at first by the Paris-Orleans Railroad and by the State Railroads. In spite of its defects it is still installed on all routes, since tests made with other proposed types have not given better results.

Second Type. (Fig. 3) This is composed of a copper cable each end of which is inserted into a split hollow copper cone. A

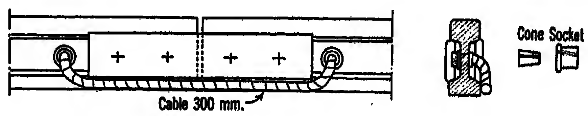

FIG. 3—RAILROAD WEDGE, CONE CONNECTION

hole is drilled on either side of the joint into which is inserted a Pairard compressive socket—a cylindrical socket, which is applied to the outside of the web of the rail. This socket is of copper and is split. The hollow cone is forced into the socket by hammering. Compression of the conductor in the cone is thus produced, as well as compression of the cone in the cylindrical body of the socket and that of the socket in the hole in the rail. In order to increase the compression, the interior and exterior walls of the hollow cone are corrugated.

The precautions necessary in installation are the same as those of the preceding type and the installation is as simple.

From the point of view of the value and permanence of contact, this type presents the same limitations as the preceding type. Since there are more contact surfaces it permits greater opportunities for corrosion. The cone is of copper; the compression of the socket on the rail is thus less than that obtained on the terminal by means of the steel pin. On account of the lighter compression, and also because there are in series six frictional contact resistances, the electrical resistance is greater than that of the preceding type, which presents but four resistances in series, of which two are friction contact resistances and two are welded contacts.

This rail bond, as liable to damage as the preceding type and presenting the same chance for theft, is in addition less desirable from the viewpoint of electric resistance, permanence of contact and durability in service. It is not employed for the original track installation, but has been adopted by the Paris-Orleans Railroad as a means of salvage of cable from rail bonds of the preceding type after the terminal has been destroyed.

Third Type. (Fig. 4) This consists of a copper cable 176 sq. mm. (0.27 sq. in.) cross section, each end of which is equipped with a terminal consisting of a simple drilled lug. A hole is drilled in the web of the rail at either end of the splice plate.

In direct attachment of this kind the contact would rapidly become poor on account of corrosion. By inserting an amalgam of tin between the copper of the terminal and the steel of the rail, the contact is greatly improved, for the amalgam penetrates all the interstices and forms a protective covering on the copper and the steel of the parts in contact, thus delaying corrosion. In order to facilitate tightening, steel washers are installed between the web of the rail and the nuts.

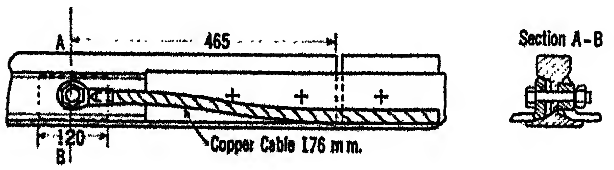

FIG. 4—BOLTED LUG CONNECTIONS WITH USE OF AMALGUM (FAYET-CHAMONIX LINE)

The terminals should be of pure copper and not of bronze or brass; otherwise the structure may become spongy under the action of the amalgam. It may be cast, but in that case a good contact should be assured between it and the cable.

The results in service are good. Installation and maintenance requirements do not interfere with traffic. Cumbersome tools and skilled labor are not required. On the other hand, this type presents the same danger of physical damage and the same opportunity for theft as do the preceding types.

This type has been adopted by the Paris-Lyons-Mediterranean Railroad for one of its electrified lines (Fayet-Chamonix).

Fourth Type. (Fig. 5) This comprises an ordinary splice bar, to each end of which is electrically welded a group of 34 strips 12 mm. (0.5 in.) wide and ½ mm. (0.02 in.) thick and 12 cm. (4.7 in.) long, arranged horizontally. The other ends of these strips are fastened to a copper terminal drilled in the center. This terminal is fastened to the web of the rail by a bolt; between the terminal and the web of the rail a tin washer is installed to assure a good contact.

The installation and maintenance do not interfere with traffic and the tool equipment is not cumbersome; furthermore, skilled

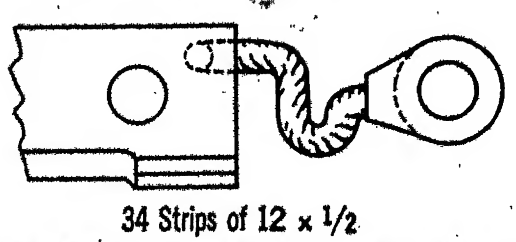

FIG. 5—ELECTRIC CONNECTION TO THE SPLICE PLATE

labor is not required. There is involved the risk of theft as with the preceding types, and a bond may be injured by track workers. The resistance value is on the order of two meters (6.6 ft.) of standard rail.

This type has been adopted by the Paris-Lyons-Mediterranean Railroad for one of its electrified lines (Culoz-Modane).

Fifth Type. (Fig. 6) This comprises a cable equipped at each end with a copper or bronze terminal which is welded to the head of the rail. The welding is accomplished by means of an oxy-acetylene flame with bronze welding rod, and while it does not require cumbersome material it does require the employment of skilled labor.

The electrical resistance of the rail bond as installed (with splice bolts tightened) is equivalent to that of 1.5 meters (4.9 ft.) of standard 46 kg/meter (92.7 lb. per yard) rail.

The danger from theft is reduced because the length of cables is only about fifteen cm. (5.9 in.). But this type of bond may be criticized in that it is open to mechanical danger caused by the passage of trains. Furthermore, the high temperature to which it is necessary to bring the rail and the weld may modify the constitution of the rail and impair its mechanical qualities. Finally, it is in the way of removal of the splice bars.

The Paris-Orleans Railroad has had about a hundred in service for about a year on the Paris-Vierzon line, and these have proved satisfactory.

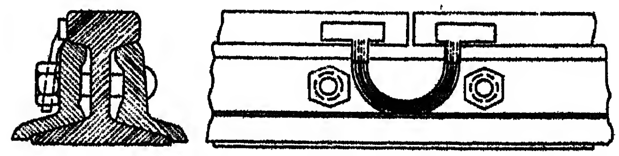

FIG. 6—WELDED CONNECTION TO HEAD OF RAILS

Sixth Type. (Fig. 7) The Briois-Bertrand rail bond comprises three strips of copper of the width of the base of the rail, perhaps 132 mm. (5.2 in.), an average length of 530 mm. (20.9 in.), and each strip of a thickness of about 1 mm. (0.04 in.). They are placed under the base of the rail, between the rail and the ties and are pressed against the rail by the tightening of the rail spikes. Between the ties the strips are formed into a bend, which allows expansion due to temperature changes. The copper conductor is made up of several strips in order to give the whole bond more elasticity. If a strip of 3 mm. (0.12 in.) thickness was used, this single strip would break at the bottom of the bend, as has been shown by tests carried on by the Paris-Orleans Railroad Company.

In order to insure that these strips do not slip under the action of motion caused by the passage of trains, each of the two halves fastened between the base of the rail and the tie is drilled with eight holes countersunk at 90 deg., 3 mm. (0.12 in.) in diameter. Into each of three of these holes is riveted a plug 3 mm. (0.12 in.) in diameter. The plugs penetrate the wood of the tie and prevent slipping. Into the five other holes rivets are placed which assure contact among the three strips and prevent the shearing of the plugs.

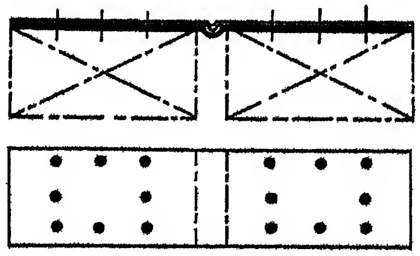

FIG. 7—CONNECTION *B B* (THREE STRIPS)

The tightening of the track spikes is of great importance in the value of the contact. The electric resistance of this type of rail bond, with the splice bolts tight, is equivalent to between one and three meters (3.3 to 9.8 ft.) of standard rail of 46 kg. per meter (92.7 lb. per yard).

The surface of the rail making contact with the copper strip should be as clean as possible and free from dampness. The bottom of the rail should be cleaned with a file.

This type offers great simplicity of installation; it is not necessary to employ special tools or skilled labor. The manufacture is easy and risks of theft are eliminated. But on the other hand,

it necessitates loosening the tie spikes, which may be a serious disadvantage where installation is made on a line on which dense traffic is maintained. The electric resistance depends largely on the degree of tightness of the track spikes.

Before a decision can be reached as to its merits, it will be necessary to know the results which the rail bond is to give in service. The Orleans Railroad Company installed 1000 on the Paris-Vierzon line some months ago.

Seventh Type. (Fig. 8) The Coullié rail bond differs essentially from those described above in that it contains no part of copper. It is a short mechanical splice bar with two bolts having a special shape, shown in Figure 8. Once installed the bar is in

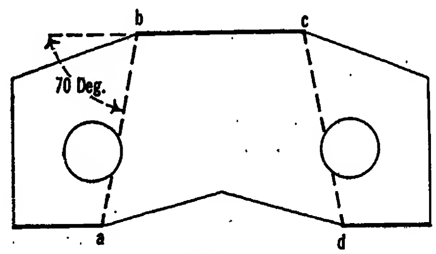

Fig. 8

contact with the head and flange of the rail along its upper and lower edges, indicated by the heavy lines. On account of the shape of the splice plate, complete tightening of the joint would make the rails (freed from all attachments) take the position indicated in Figure 9. On a track equipped in service, this lifting is very slight—1 or 2 mm. (0.039 to 0.079 in.) above horizontal;—the ends of the rails thus elastically deformed tend to assure their normal horizontal positions. The result is a free and permanent contact between the parts shown at A, B, C and D (Fig. 9). At each passage of a locomotive or car the angle $X\ O\ Y$ opens a little and then assumes the initial position. The joint is elastic; the ends of the rails are lowered together the same distance under the effect of the load without producing the slightest space between the plate and the rails. The shocks which are produced when a wheel passes over the joint are no longer experienced. The passage is indicated only by the inevitable noise which results from the gap between the rails.

Finally this rail bond offers an excellent electric conductivity on account of the permanence of its contact with the rails. This is attained without the use of special contact devices which are

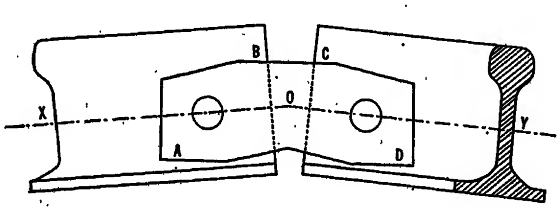

Fig. 9

always costly to install and maintain. On account of its design it produces a very good contact when there is nothing passing on the track, and when equipment is passing, this contact is improved by the pressure on the rail. The electric conductivity is preserved, thanks to the cleaning which is produced at A, B, C and D at each passage of a wheel on account of the automatic opening and closing of angle $X\ O\ Y$ already seen in Fig. 9. When a rail joint is dismantled the surfaces in contact are bright. The resistance of the rail bond when there is no load on the rail is equivalent to 2.5 to 3 meters (8.2 to 9.8 ft.) of standard rail.

The bolts used with the rail bond should be provided with locks so the nuts cannot come off. To accomplish this the Midi Railway Company has successfully utilized the Montupot locknut shown in Fig. 10.

This type of joint possesses numerous points of superiority as compared to others.

Its position is the most simple and consequently the most economical that can exist. There is no necessity of heavy and cumbersome installation equipment, neither does it require the employment of skilled labor.

It does not interfere with traffic.

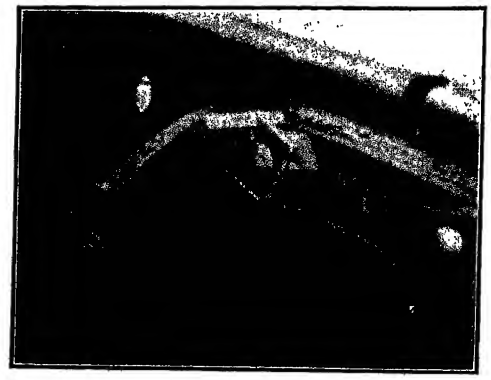

Fig. 10

It is not exposed to damage by tools of track workers and there is no danger from theft.

The contact preserves its value in a permanent manner, and is not impaired by work on the track or by atmospheric conditions.

Its price is less than that of an ordinary mechanical rail joint, for it is much shorter and requires fewer bolts.

For these reasons, after the results obtained at the end of a year of test the Midi Railroad decided to equip all its road—electrified or not—with the Coullié rail joint. On electrified lines the old rail bonds have been progressively removed. The Coullié rail bonds have been installed on more than 500 km. (310.69 miles) of track and by reason first of the low cost of this joint and the low expense of installation, and second of the possibility of salvage of copper from old rail bonds, it happens that the opera-

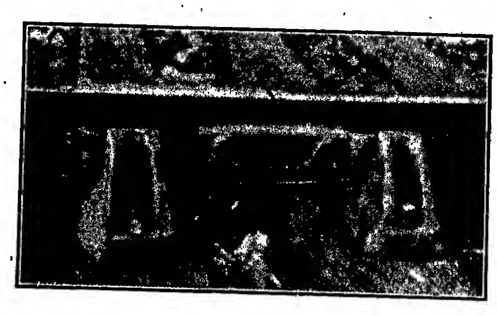

Fig. 11—View Taken of the Midi Railroad System

tion of substitution of the Coullié rail bonds for old ones is an economy rather than an expense. By its superiority, electric as well as mechanical, this rail bond is now the standard for electrified and non-electrified tracks on the Midi Railroad. It is possible that this new rail bond, which produces the best results, will be used in the future on other systems. The Compagnie du Chemins de fer Economiques de la Gironde has already undertaken preliminary tests and the results have been so satisfactory that it has adopted the joint for its lines and several thousands of Coullié joints have already been installed on its system.

In conclusion it may be said that on a section of line of 20 km. (12.4 miles) equipped with this type of rail bond, the Midi Rail-

way Company has experimented by removing copper connections installed between rails for electric signaling, and their experience has proved that electric signaling functions better on lines equipped with the Coullié rail bond without special connections than upon lines not equipped with Coullié rail bonds and with special connections. This produces a new economy and an appreciable simplification.

The Coullié rail bond is the only type which has given practical results sufficiently well enough to definitely determine its adoption. The other types of rail bonds comprise either material under test or material which was adopted at the time of electrification, only because the most satisfactory material was not then available.

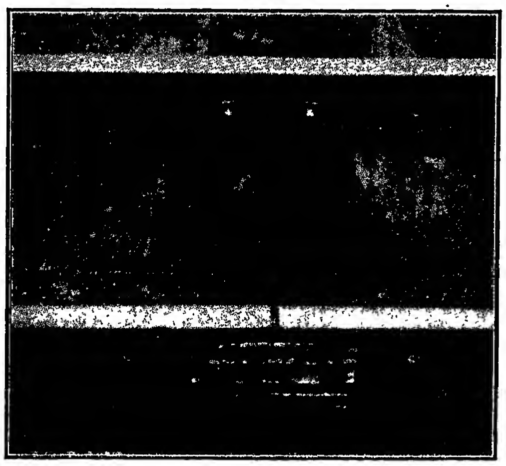

Fig. 12

I. W. Wechmann: Bonds in the rail return circuits are used only on the 800-volt d-c. lines in the Berlin suburban service. On the trunk lines, electrified with 15,000-volt, $16^2/_3$ cycle current, bonds have hitherto been found unnecessary either to reduce voltage drop or to mitigate interference with communications circuits.

The continuous connection of the ends of the rails is accomplished in several ways, as follows:

(a) Zinc spraying the surface of the splice bar and its seat on the rail.
(b) Zinc spraying the splice bar and "roll zincing" the seat.
(c) Welded bonds.
(d) Bonds with driven terminals.
(e) Bonds with conical screw terminals.

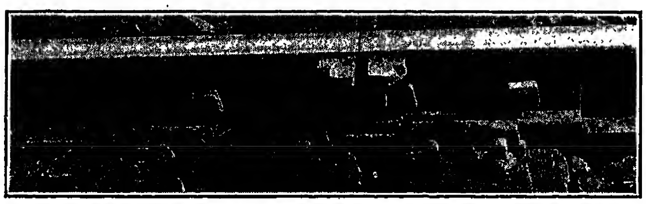

Fig. 13—Welded Bond Cross-Section. 95 Sq. Mm. (0.14 Sq. In.)

(a) The Meurer process zinc sprayed joint was adopted on all lines which were subject to rail renewals before the Berlin electrification, and also on such lines as were already electrified whenever there was rail renewal. The zinc sprayed joint, which has good conductivity with careful maintenance, originally was to have become the standard for electrified sections. Standardization has, however, been delayed because the conductivity has decreased considerably after a comparatively short time. The majority of the joints show only slight traces of the zinc after two to two and a half years' service and have a conductivity equivalent to 33 ft. or more of rail. (A new joint has the equivalent of about 6 to 10 ft.). Zinc sprayed joints will thus be used only when individual rails are replaced in sections where those joints are in use.

(b) With the rolled zinc joint the angle bar is sprayed with zinc, while the rail seat is given a coating of zinc-tin alloy after a cleaning and roughening of the surface by means of a milling rack. This coating is rolled on to the cleaned surfaces of the rail seat by a roll on a flexible shaft driven by a motor. The rolled zinc joint has been used only in an experimental way on a short section which has been in service for but a brief time. It had initially a satisfactory conductivity which fell sharply, however, after a short time because the zinc-tin coating worked off the rail.

Fig. 14—Welded Bond. (U Bond) Cross-Section 95 Sq. Mm. (0.14 Sq. In.)

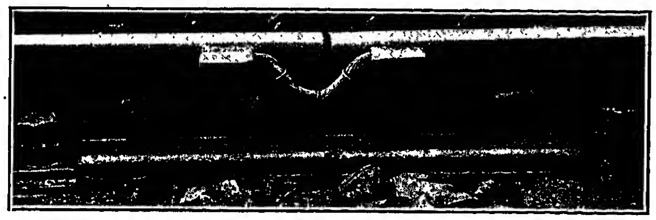

Fig. 15—Welded Bond (Embru) Cross-Section 95 Sq. Mm. (0.14 Sq. In.)

Fig. 16—Bond With Driven Terminals Outside the Angle Bar Cross-Section 95 Sq. Mm. (0.14 Sq. In.)

(c) Welded bonds so far have been used in three forms. Fig. 13 shows the oldest development, which has been given up because the U-shaped copper strand, which was welded into the iron rail head welding terminal, broke at the point of welding.

The bond pictured in Fig. 14 does not have this disadvantage. In this case iron sleeves are pressed in terminals which are welded to the rail head. This type of bond was used only in small numbers because its conductivity was somewhat less than the "Embru" bond shown in Fig. 15. In addition, it has a disadvantage in the fact that it can be installed only once and when replacement is necessary has value only as scrap. A further point against general installation of this type with addition of the pressed iron sleeve is that in a short time the inside rusts and thus

the life of the bond is shortened. Experience has shown that this modification was an error.

The "Embru" bond (Fig. 15) can be used several times if it is carefully handled during replacement. The iron terminal which is welded to the rail head is galvanized internally and in addition is welded at the end with the copper strand. Its conductivity is good, equivalent to three or four feet of rail.

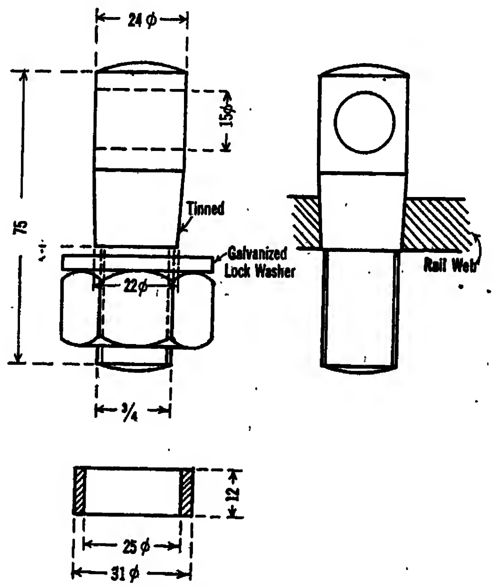

Fig. 17—Railbond

Welded bonds were used, with the few exceptions noted, for all electric traction rails and rails used for a negative return which were not relaid with zinc covered rail ends before the beginning of the electrification.

The greatest objection with the welded bonds is the difficulty of welding replacement bonds. This work can be done only at night and if only a few are to be replaced the costs are high. For this reason no welded bonds will be installed with future rail renewals.

(d) The future standard can be seen in the bond with driven terminals shown in Fig. 16. It can be installed without difficulty in the daytime. Furthermore, it can be used at least twice with the exercise of care. This type only will be used in equipping urban railways, because it seems to be suited to such conditions. It will also be used at switches on the sections which are equipped with welded bonds, because easy replacement of bonds facilitates the renewal of switch parts.

(e) The bond with the conical screw terminal has a conical galvanized iron terminal instead of a driven copper terminal. This type can be changed often and has been used with success as replacement for driven terminal bonds where individual rails or switch parts are replaced as frequently as three months.

The preceding discussion relates exclusively to longitudinal bonds. For cross bonding the type with driven terminals described under (d) is used.

Guiseppe Tronconi: These bonds (Fig. 18) are standardized on every system of electrification in use in Italy.

H. F. Brown: Mr. Febrey in his discussion presents the manufacturers' point of view and some of their problems, which are always of great interest and value to those who are responsible for the application, operation and maintenance of rail bonds as well as any other product. His remarks relative to the necessity for simplification of bond design and elimination of some of the many processes now used for applying welded bonds, are very timely, for a great deal of study is being given at the present time to these very points by various committees of the American Electric Railway Association and the American Railway Association, with every indication that some of these desiderata will be attained in the near future. Simplification and standardization cannot fail to produce not only a better article, but a cheaper one as well.

The data contributed by Messrs. Müller, Ofverholm, Parodi, Wechmann and Tronconi are of extreme interest and importance, in that a very complete resumé of European practise is given. It

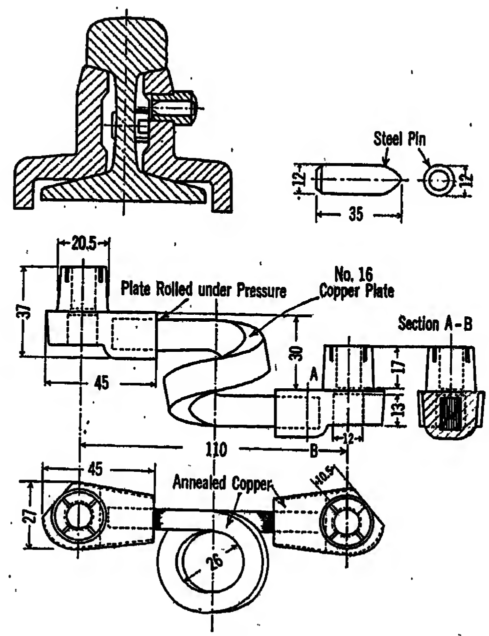

Fig. 18

is interesting to note that in general this is similar to our American practise, with the exception of the use on the French Railways of the Coullié Joint (sometimes called the "chevron joint"). So far as I know, this has not been tried to any extent in this country. It would be of interest to know just how long such a rail joint would last without excessive maintenance under the heavier axle loadings and on the larger rails in general use in America.

An Electron Tube Telemetering System

(Part I)

BY A. S. FITZGERALD[1]

Member, A. I. E. E

Synopsis.—The paper describes a varying frequency telemetering system which employs an electron tube beat frequency oscillator, the frequency of which is controlled by a small condenser mounted upon the movement of the instrument, the reading of which is to be transmitted. The reading is reproduced at the receiving end by a frequency meter having a scale corresponding to that of the transmitting meter. The outstanding feature of this system, when furnishing a single indication, is that, except for the movements of the transmitting and receiving instruments themselves, there are no contacts or moving parts. The system does not require instruments of unusual type, and it is not limited to the transmission, only, of electrical readings, but may readily be applied to any deflection instrument indicating, for instance, pressure, temperature, etc. The accuracy of the system is not affected by changes in the impedance of the channel of transmission. The system is equally suitable for transmission over wire conductors or by means of carrier current or radio.

A method of furnishing a number of telemetering indications over a single conducting circuit or carrier-current channel, is also described, which uses automatic telephone type selectors at transmitting and receiving stations. A feature of this system is that no synchronizing channel or synchronous power is required. By a system of impulses, the selectors automatically establish and maintain synchronism.

A field installation which has given satisfactory results is described.

INTRODUCTION

General. Recent developments in power system operating methods, especially in the direction of remote and automatic control of apparatus in distant stations, make it increasingly necessary that the load dispatcher be fully informed as to the load conditions at remote parts of his system.' This paper describes an attempt to furnish a method of telemetering of more general scope than existing schemes and which it is hoped may prove especially suitable for application on large interconnected systems.

The basic problem is to make available, at the required location, one or more instrument readings relating to the power conditions at some remote point. An elementary step in this direction is to extend secondary connections from a current transformer at one place to an ammeter at another. The limitations of this principle are obvious. What we have to do in order to realize a successful telemetering system, suitable for general application, is not to transmit the power to be indicated and to measure it at some remote location, but to measure the electrical conditions where they occur, to convert this measurement into some electrical effect, transmit this as far as may be necessary, and then to translate this effect back into a visual or a graphic reproduction of the original indication.

This effect, which is to serve as the vehicle which carries the telemetering indication, must be determined with special reference to the channel over which it is to be transmitted. Many of the existing systems of telemetering require a special wire line. Some of these are influenced, in respect of their accuracy, and thus limited in scope, by the resistance, impedance or insulating properties of the connecting circuit. In the present system it has been felt desirable to avoid a vehicle involving any definitely quantitative electrical effect, but rather to employ one which will, as far as possible, be independent of the nature of the channel over which it is transmitted and of the conditions of the channel.

If we will ask ourselves the question as to what electrical effect can best be transmitted over an unlimited distance, over a channel of undetermined and possibly variable impedance, taking into account leakage or attenuation and possible inductive interference, *without loss of identity,* we shall clearly perceive the fundamental requirements of a telemetering system. If we further consider what kind of effect can readily be controlled by an instrument deflection and can as easily be translated back into a scale reading, it will become evident that a frequency system offers the best promise of furnishing the characteristics required.

A frequency can as readily be transmitted by a conducting circuit, by radio, or by carrier current; even by a light or sound channel if necessary. And, provided that transmission be actually accomplished, the frequency received can hardly be other than that which is sent out, even though a high order of extraneous variations in transmission efficiency. or of interference, be present.

We will therefore employ a frequency as the vehicle by means of which the instrument reading is conveyed from one place to another. When the load—or whatever it is that is to be metered—is small, a low frequency will be transmitted. As it increases, a frequency proportionately greater will be sent out. By directly measuring the frequency which is received, the magnitude of the distant instrument reading can be ascertained.

How such a frequency may be generated and controlled, and what order of frequency will be suitable, will now be considered.

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1. Engg. Dept., R. C. A. Victor Corp., Camden, N. J. Formerly with the Radio Engg. Dept., General Electric Co., Schenectady, N. Y.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

Principle of Operation

Most of the existing systems of telemetering require more or less cumbersome additional apparatus for the purpose of translating the instrument reading into the electrical effect which is to be transmitted. In general, some such device as a motor-operated follower movement which will reproduce the position of the instrument pointer is usually necessary. It will be an advantage if such methods can be avoided. A means of converting an instrument reading directly into a corresponding frequency without the necessity for additional mechanical moving parts will be distinctly preferable.

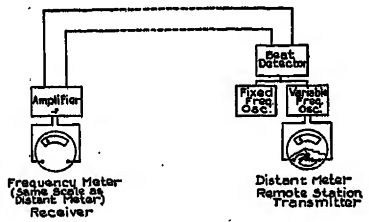

Fig. 1—Transmission Over Wire Conductor

The electron tube oscillator immediately suggests itself as a method of frequency control. It has been proposed by St. Clair, and others, that a condenser be attached to the instrument which it is desired to telemeter and that this be connected in the circuit of an oscillator in such a way as to influence the frequency at which it will oscillate. One of the special features of such a method is that it is not restricted to the telemetering of electrical quantities, as are some systems. It is controlled simply by mechanical or angular displacement and may thus readily be employed in connection with any measuring or indicating device furnishing a deflection.

The range of frequency which may be used depends both upon the permissible dimensions of the control condenser and upon the characteristics of transmission of a-c. energy over the channel to be employed. If we furnish a measuring instrument, such as a voltmeter, wattmeter, etc., of conventional type and of robust construction, it will be found that a condenser of the order of 0.0005 microfarads can readily be mounted on the movement of such a meter without interfering in any way with its accuracy or operation. Such a condenser is capable of controlling frequencies of the order associated with carrier current or radio circuits. A condenser suitable for controlling very much lower frequencies would be too bulky to attach to any ordinary meter.

The use of a high frequency, varying according to the meter position, as the vehicle for transmitting the instrument reading, would be attended by difficulties both in transmission and in furnishing a direct indication at the receiving station. With frequencies of this order, transmission would be very largely affected by the change in frequency resulting from the meter movement. For transmission over wire conductors, the attenuation would be considerable. Transmission of carrier can be readily obtained over high-voltage power lines, at one definite frequency, by properly tuning the coupling circuits and by selecting a frequency which conforms to the constants of the transmission line. But since this involves a number of adjustments, all depending upon frequency, it would be very difficult indeed to transmit carrier having a widely varying frequency. The result would be that wide variations in signal strength would occur with changes in the instrument reading. Furthermore, no simple instrument which will give a direct indication of a high frequency, is available.

Thus it is necessary to employ a frequency which can readily be transmitted over a metallic conducting circuit without either serious attenuation or marked effects due to resonance, and for which a direct reading frequency meter can easily be furnished. This therefore suggests a frequency of the order of hundreds, rather than thousands. Such a frequency may be transmitted readily by a simple wire circuit.

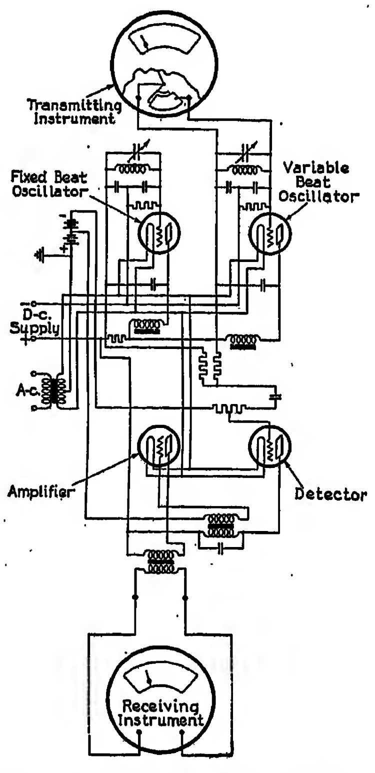

Fig. 2—Diagram of Connections

If it should be desired to transmit the telemetering frequency over a high-voltage power line, by means of carrier current, this can be done by exactly the same methods as are employed for carrier-current telephony. The carrier wave is modulated with the telemetering frequency instead of by speech frequencies. In this way the telemetering frequency is not directly associated with any problems in connection with the transmission of the signals over the power network. That is,

it does not in any way restrict or interfere with the selection of the carrier frequency, which must largely be governed by line constants and characteristics, in accordance with which the carrier circuit must be adjusted and tuned.

Telemetering Single Instrument Reading over Conducting Circuit

Fig. 1 shows the general arrangement which is employed. A small condenser is attached to the movement of the instrument of which the reading is to be telemetered. This condenser is connected to an oscillator so that the frequency of the latter varies according to the meter position. The frequency of the oscillator will be high—comparable with a carrier frequency—and the change in frequency corresponding to full scale deflection will be less than ten per cent. The force due to the electrostatic attraction between the

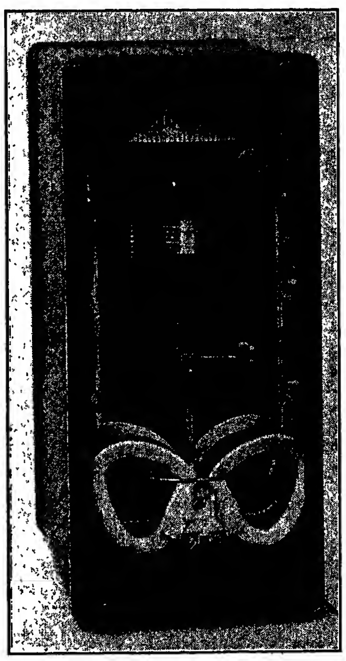

Fig. 3—Transmitting Instrument

condenser electrodes is, in comparison with the meter torque, negligible.

A second oscillator, operating at a frequency close to that of the first oscillator, has a fixed condenser, and therefore furnishes a constant frequency. A beat frequency is set up by these two oscillators and this is detected by means of a third vacuum tube. This beat frequency will be relatively low, and it will vary, in accordance with the instrument deflection, over a suitably extended range which may amount to a hundred per cent or more.

The beat, or telemetering frequency, is transmitted, over the connecting line, to the receiving station, where it operates a direct reading frequency meter. The frequency meter may be directly energized by the incoming signal or an amplifier may be provided. This will depend upon the nature of the line, its impedance, and on the energy level which it is permissible for it to carry.

The frequency meter will be furnished with a scale corresponding exactly with that of the distant instrument. It will indicate at all times exactly the position of the remote instrument and will follow all such changes and fluctuations as the damping of the transmitting instrument permits the latter to follow. The receiving instrument has the usual characteristics of such meters, that is, its indication depends upon frequency

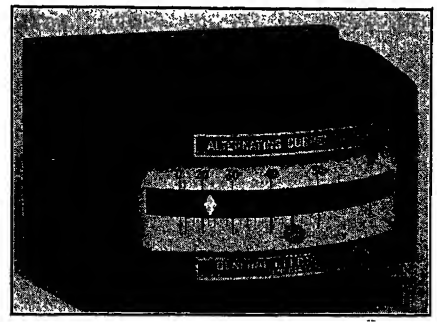

Fig. 4—Receiving Instrument

only and, provided it receives more than the minimum power necessary to operate it, is not affected by changes in signal strength. Thus, any changes in the impedance or leakage resistance of the line do not affect the accuracy. Moreover, inductive interference is more likely to affect the signal strength than it is to produce any effects tending to change the frequency.

Fig. 2 is a complete diagram of the connections at both transmitting and receiving stations. Fig. 3 is a typical transmitting instrument and Fig. 4 one of the receiving frequency meters.

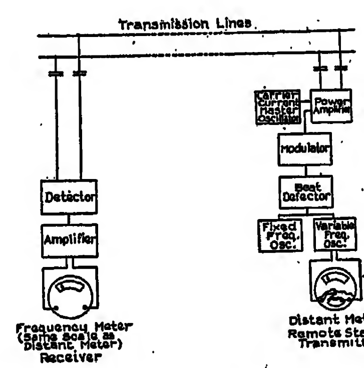

Fig. 5—Transmission by Means of Carrier Current

Carrier-Current Transmission

If it is desired to transmit the instrument readings by carrier, either over special conductors, telephone lines, or high-voltage power lines, this is done by employing transmitting and receiving apparatus very similar to telephone communication equipment which is already familiar in central station engineering.

Fig. 5 shows a schematic diagram of the general arrangement for carrier-current telemetering. The

complete connections at the transmitter are shown in Fig. 6. The beat frequency is applied in the regular way, to the modulator, instead of a microphone speaking circuit. The carrier-current generator consists of the usual arrangement of master oscillator and power amplifier. There is thus sent out over the line a carrier wave of steady carrier frequency which is modulated by

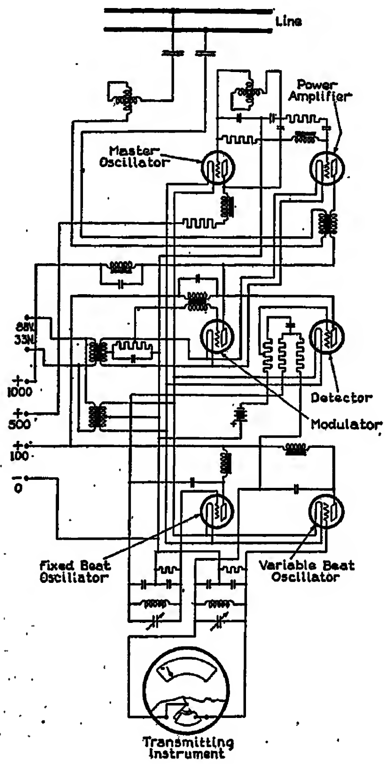

FIG. 6—DIAGRAM OF CONNECTIONS OF CARRIER-CURRENT TRANSMITTER

an audio frequency which varies according to the position of the instrument which is being telemetered.

At the receiving end, the connections are as given in Fig. 7. The carrier is demodulated and the audio signal amplified. The amplified signal is then taken direct to the frequency meter which thus reproduces the position of the distant instrument. It will be especially noted that again the signal strength—provided it be sufficient to energize the apparatus—has no effect upon the accuracy of the indication.

MULTIPLE TELEMETERING

In many cases it will be desirable to telemeter more than one instrument reading from a remote station. There is a number of different arrangements which may be provided, depending upon the circumstances and requirements.

Two or three indications, for instance, may be sent over the same channel simultaneously by assigning to each instrument a different range of frequency. At the receiving station, these frequencies may be unscrambled by means of band pass filters. Thus, one instrument may work from 300 to 600 cycles, another from 800 to 1600, and a third from 2000 to 4000.

However, one cannot very conveniently read more than one instrument at a time and in the majority of cases it is not essential that this be done. Thus, in general, it is entirely satisfactory if the different readings be furnished selectively one after the other. In this way a larger number of instruments may be telemetered than could be done simultaneously.

A telemetering system is a convenient and desirable adjunct to any system of supervisory or remote control. Almost, one might say, a necessity, if the full value of the control system is to be realized. One very simple method of telemetering a number of different instruments over a single telemetering channel, is to make use of the supervisory apparatus in such a way that the operator can, at will, cause any distant instrument to be connected to the telemetering transmitter so that it assumes control of the indicating frequency. At the same time, a suitably scaled instrument will be connected to the telemetering receiver.

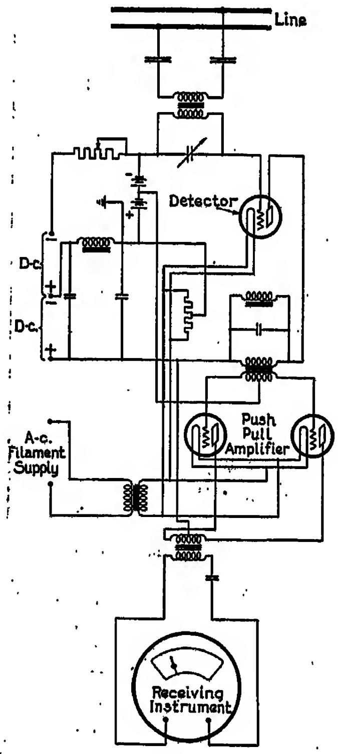

FIG. 7—DIAGRAM OF CONNECTIONS OF CARRIER-CURRENT RECEIVER

Another alternative is to employ a dial telephone installation in a similar way so that the operator, in order to obtain the reading of any remote instrument, will dial a specified number which will cause this instrument to be connected to the telemetering equipment.

For load dispatching and other important services where it is desirable for the operator to be able to see, at a glance, the state of the system in general, an arrangement has been devised by means of which, over a single telemetering channel employing one transmitting equipment and one receiver, a number of instruments at one

station may be continuously indicated in the load dispatchers office. This may be carried out with equal convenience either over a wire line or by means of carrier equipment over the power conductors.

According to this system, there is provided at the remote station, a continuously operating selector which automatically connects each instrument, one after the other, to the telemetering transmitter for a brief period. Twenty or more instruments may be taken care of in this way.

At the receiving station, there will be installed an equal number of instruments. These will all be frequency meters identical in construction but each will bear a scale representing the corresponding instrument

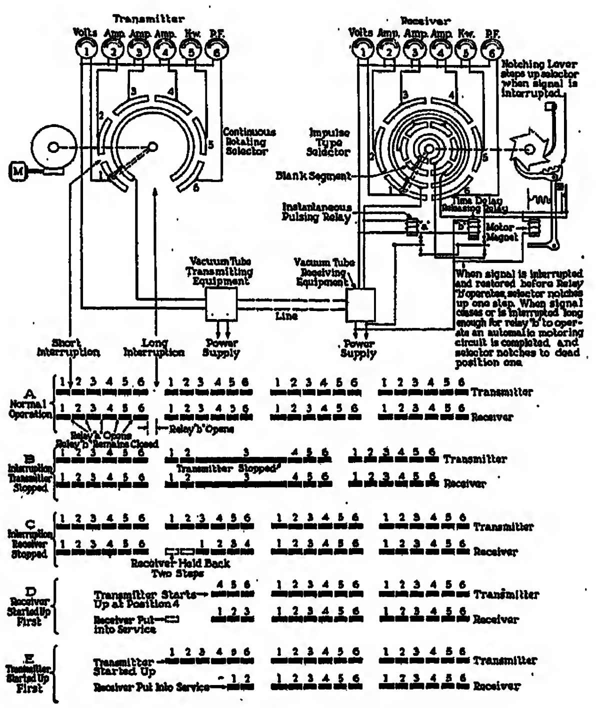

FIG. 8—METHOD OF SYNCHRONIZING MULTIPLE TELEMETERING SYSTEM

at the remote station. A second selector associated with the receiver is arranged to connect each receiving instrument to the telemetering receiver during exactly the correct period at which the corresponding remote meter is connected, by the transmitter selector, to the telemetering apparatus, and has control of the indicating frequency. Thus, each pair of instruments, one transmitting and one receiving, is given possession of the telemetering channel once in each complete cycle, which embraces all of the instruments. The receiving instruments which are employed with this system of telemetering have movements of the type which retain their position when deenergized. Thus, when they are operated in this manner, we get the following result. Each instrument indicates at all times the reading shown when it was last connected to the telemetering circuit. At regular intervals, each meter is corrected. Thus, if we assume that each instrument is energized for a second, which is sufficient for it to assume, and come to rest at, its corrected reading, each reading will be checked about every ten seconds if there are ten instruments. With other numbers of meters, the frequency of correction will vary accordingly.

The result will be that all the instruments, all the time, will show the state of the power system, at most, ten seconds previously. Thus a survey of the whole set of meters will furnish, very nearly indeed, as good an idea of the operation of the distant station as if one could see the remote instruments in actuality.

Clearly it is necessary to synchronize the selector at the receiving station with that at the transmitter. A feature of this scheme which is of special interest is the fact that, unlike many existing methods of synchronizing, it does not require a special channel for this purpose. No extra conductors, or additional carrier-current circuit are necessary. Nor is it necessary to perform any special operation when the apparatus is placed in service in order to synchronize the two selectors. Thus, it is no more difficult to operate multiple instrument telemetering over carrier or radio than over a wire line.

How this has been accomplished is shown in Fig. 8. This diagram has been prepared primarily in order to present an explanation of the principle on which the synchronizing system operates. Thus it does not purport to represent the type of apparatus employed nor the actual connections. In order to simplify the diagram, only six instruments are drawn, but it is to be understood that exactly the same principle of operation may be carried out with any greater number of meters.

At the transmitting station, the selector, continuously operated by any suitable means, connects the instruments one after the other to the telemetering transmitter. The energy sent out by the latter, either in the form of ordinary alternating current or carrier current, as may be employed, is interrupted for a brief period each time the selector steps from one segment to the next.

At the receiver, the selector has a similar number of segments. But instead of being continuously rotated, it is actuated by a step-by-step mechanism. Each time the telemetering energy is interrupted and instantly restored, operating the pulsing relay *a*, the selector notches up one step, thus transferring the received energy from one meter to the next in synchronism with the transmitter selector.

This is evidently entirely satisfactory if both the selectors are started up properly in step and if nothing happens which may interfere with this regular step-by-step operation. But it is well known that any simple notching scheme, without any additional synchronizing feature, is not suitable for continuously maintaining two different pieces of apparatus in step. In the event that the step-by-step mechanism should slip a notch, or should pick up additional impulses due to external inter-

ference, cumulative errors, which are inadmissible, are liable to occur. The present system has been devised with a view to providing, without any additional synchronizing channel, a method of preventing such effects from producing any cumulative discrepancies. This is accomplished as follows.

After the last instrument in the group has been telemetered, the transmitter selector returns to the first segment. But before it does so, the transmission is interrupted for a period somewhat longer than the normal break when transferring from one instrument to the next. The receiver selector is furnished with an additional time delay releasing relay *b*. This does not have time to re-set during the regular interruptions which occur when the transmitter selector moves from segment to segment. But during the long break which occurs immediately following No. 6, relay *b* operates. This completes what is called the "motoring circuit" through the motor magnet, which notches up the selector, and the inner range of segments on the selector which are furnished for this purpose. All of the segments are connected together except No. 1. This causes the selector to "motor," that is, it is continuously notched round until it reaches the blank segment No. 1, on which it stops. Thus, when the telemetering signal ceases entirely, or is interrupted long enough for relay *b* to re-set, no matter upon which segment the receiving selector may be, it is instantly returned to the first segment and meter No. 1 is connected to the receiver. It will normally be at rest in this position, therefore, when the apparatus is not in service.

The transmitter, it has been noted, always gives a long interruption immediately before moving on to segment No. 1. The receiver is automatically returned to the same position by the long interruption. Therefore, immediately following this interruption, both selectors are in synchronism and meters No. 1, both transmitting and receiving, have possession of the telemetering channel.

In Fig. 8 an attempt has been made to indicate graphically the operation of the selectors. The interrupted lines indicate when the telemetering energy is, respectively, being sent out by the transmitter and is energizing the receiver. The numbers indicate the segments which are occupied by the selectors and show when the two are in synchronism.

A shows entirely normal operation, the transmitter is on segment No. 1 and the receiver also is connected to the first instrument. After the first meter reading has been telemetered and the instrument at the receiving station has been energized for about a second, long enough for it to come to rest in its corrected position, the transmitter selector moves on to No. 2. In so doing, it instantaneously interrupts the signal which causes the receiver selector to notch up on to No. 2 also and the second instrument reading is telemetered. In the same way, each of the meters at the receiving station is corrected one after the other and finally No. 6 is reached. After this, the long interruption occurs and both selectors return to No. 1.

In order to better indicate the operation of this system of synchronizing, it is assumed in *B* that the transmitter selector is stopped for an instant by some form of interference. It is assumed that it is stopped while the signal is being sent out, and that this continues until the transmitter is allowed to continue its operation. It will be seen that when this occurs, the receiver is not thrown out of synchronism but that it remains on the same segment as the transmitter until this is released, when both continue in the normal manner.

In *C* it is assumed that the receiver suffers some form of interference due to which it ceases properly to notch forward. A transient short circuit on the transmission channel or loss of signal through some other cause might produce this effect. This is shown as having occurred when both transmitter and receiver are on segment No. 1. The interference does not affect the transmitter which continues to step around. The trouble ceases when the transmitter has reached segment No. 3 and the receiver thereafter notches up along with the transmitter. But it is out of synchronism and the proper instruments are not being connected to the receiver at the proper time. But as soon as the transmitter reaches No. 6, we get the long interruption before returning to No. 1. The receiver has reached No. 4. But when the long interruption occurs, the receiver immediately motors round to No. 1. The two selectors can now be seen to continue in synchronism.

It has been mentioned that no special measures have to be taken, when putting this equipment in service, in order to synchronize transmitter and receiver. This is done automatically as shown in *D*. It is assumed that the receiver is first placed in service. The selector is on segment No. 1, on which it always stops when deenergized. Since there is no incoming signal, it remains in this position. The transmitter is now started up. It may have stopped on any segment last time it was used. It is shown as having stopped at No. 4. As soon as it commences successively to connect the different instruments to the telemetering transmitter, the receiver starts to notch up, but out of step because it started from No. 1. It continues out of synchronism until the transmitter reaches No. 6, when the receiver has reached No. 3. The long interruption now occurs and both transmitter and receiver now start in synchronism on No. 1.

E shows what happens if the transmitter be started up first. The receiver is switched into service just at the instant when the transmitter happens to be on No. 5. As soon as the latter reaches No. 6, and returns to No. 1, the receiver falls automatically into step in the manner which has been described.

Thus we have an arrangement in which the receiver and the transmitter may independently be started up (it does not matter which is first placed in service) without paying any attention to the question of syn-

chronism. Within a few seconds the receiver will automatically fall into step with the transmitter. In the same way, if, while the telemetering apparatus is in service, the receiver may be thrown out of synchronism by line disturbances or interference, as soon as normal transmission is resumed, without any attention from the operator, synchronism is automatically restored.

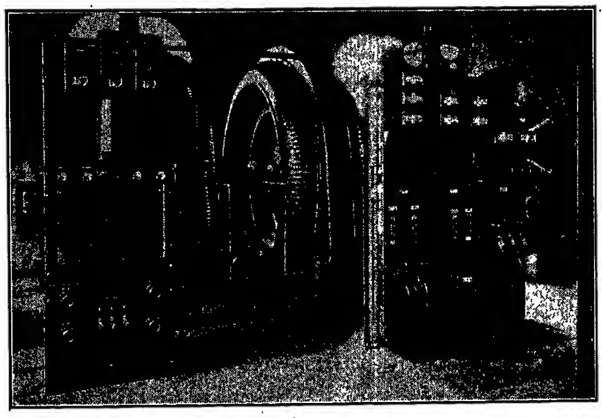

FIG. 9—INSTALLATION AT AMSTERDAM

DESCRIPTION OF APPARATUS

In order to study the operation of this system under service conditions, an installation has been made in the neighborhood of Schenectady. Instrument readings in a railway substation at Amsterdam, N. Y., and at another substation at Glenville are transmitted by means of carrier current to a receiving station on the outskirts of Schenectady.

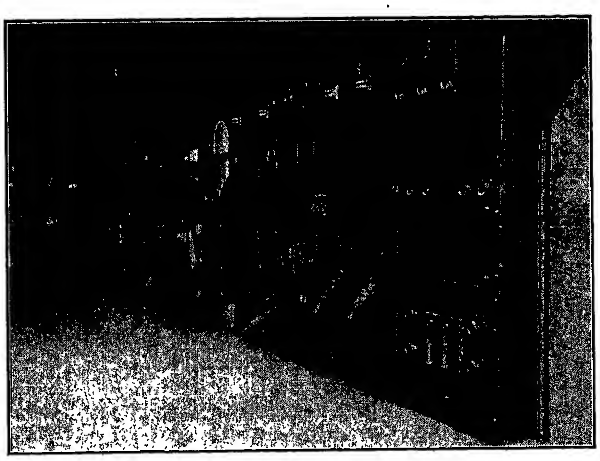

FIG. 10—INSTALLATION AT GLENVILLE

For this installation, two transmitters and two sets of receiving equipment were specially built. No attempt was made to arrive at a finished design. The necessary circuits and apparatus were merely assembled in a convenient form for carrying out an extended field test.

TRANSMITTING EQUIPMENT

Fig. 9 shows a view of the apparatus installed at Amsterdam. A view of the Glenville installation is shown in Fig. 10. Fig. 11 shows a closer view of one of the transmitters, both of which are substantially similar except for the instruments and certain details in connection with the power supply.

While the apparatus furnished is able to take care of as many as 20 instruments, it was felt that for the purpose of these tests, it would be sufficient to install three only. The carrier-current transmitter incorporated in this equipment is sufficiently powerful to send the telemetering signal a distance upward of 100 miles if necessary. For the purpose of this test, it was convenient, however, to transmit a shorter distance so that both ends of the line might readily be accessible. Amsterdam is about 20 miles from Schenectady.

The three instruments, one after another, are successively connected to the carrier-current transmitter by

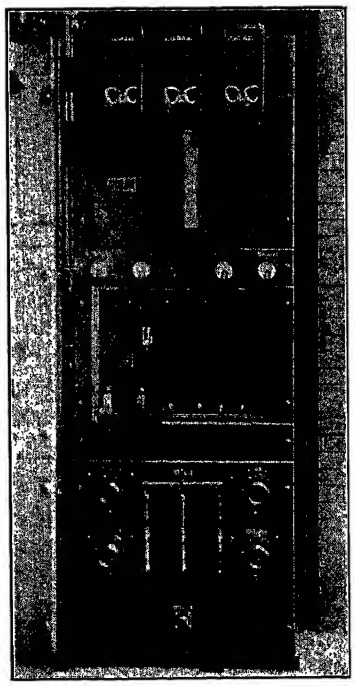

FIG. 11—CARRIER-CURRENT TELEMETERING SYSTEM

means of the special selector. This is illustrated in Fig. 12. While the general principle of operation by means of which the successive transmission of the different instrument readings is performed, is substantially that described with reference to Fig. 8, it is found convenient in practise to employ at the transmitting end a selector mechanism somewhat similar to that shown, in Fig. 8, at the receiving station. That is to say, this selector is not, in fact, continuously operated by means of a rotating drive, but is notched up successively by means of an automatic vacuum tube timing circuit. It connects the telemetering circuit to each instrument in turn for a definite period, after which it is instantly transferred to the next instrument. When the last instrument has been telemetered, it introduces a time delay exactly as described with regard to Fig. 8. The first indication is then repeated, this cycle of opera-

tion being continued indefinitely. This time delay is controlled by a vacuum tube, condenser, and high-resistance circuit of the type in which the duration of the time delay depends upon the time taken for the condenser, which is connected to the grid, to discharge through this high resistance.

Since one of the most important characteristics of this equipment, which it has been particularly important to study, is the constancy of the relation between the beat frequency of the oscillators and the position of the instrument condenser, there was introduced into this equipment a convenient method of keeping a check upon this feature throughout the test. While only three instruments are to be seen upon the panel, there are transmitted four successive indications. Three of these are the instruments shown, the fourth one is simply a fixed capacity. The fourth indication, therefore, should invariably be the same frequency.

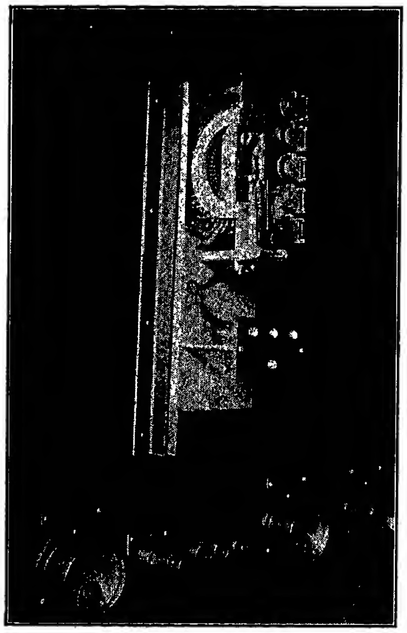

FIG. 12—TRANSMITTING SELECTOR

RECEIVING EQUIPMENT

The receiving equipment is illustrated in Fig. 13. This consists of two identical carrier current telemetering receivers, one of which, that shown on the left, receives the carrier-current transmission from Amsterdam. The right hand receiver is tuned to the carrier-current transmitter at Glenville. The power supply for the two receivers is controlled by switches mounted upon the left hand panel. Reading from left to right, the instrument indications are as follows:

Left Hand Panel Amsterdam	Right Hand Panel Glenville
A-c. feeder current	D-c. trolley volts
A-c. feeder volts	D-c. current west track
A-c. feeder kilowatts	D-c. current east track

Below each of these sets of three instruments may be seen a fourth instrument. This is not provided with any scale but is marked at one position only. This corresponds to the frequency sent out by the fixed condenser mounted in the transmitter. Thus, it has been possible to study very easily the constancy of the vacuum tube beat frequency circuit. So long as this instrument remains at the marked position, this forms a definite indication that the readings of the other instruments are exactly correct.

It also gives a definite indication that the receivers are in synchronism with the transmitters. Should the receiver get out of synchronism, this instrument will be energized with a frequency corresponding to one of the other instruments which will cause it to move away from the normal position.

Fig. 14 shows a picture of the selector at the receiving station. This selector works exactly in accordance with the one described with respect to Fig. 8.

OPERATING CHARACTERISTICS

The results obtained with this test installation have clearly shown that this system offers an entirely practical method of telemetering.

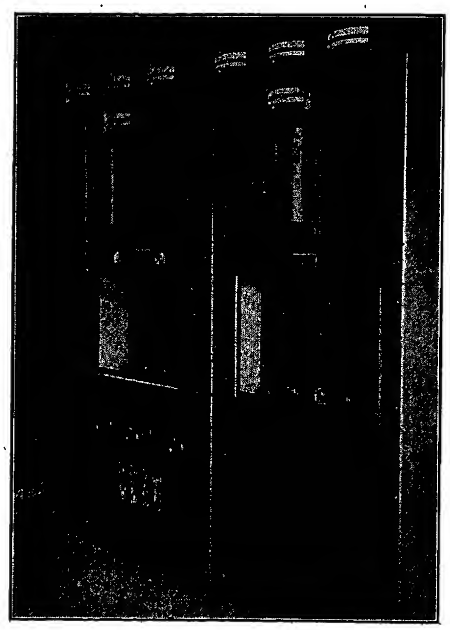

FIG. 13—INSTALLATION AT RECEIVING STATION

The outstanding characteristic which these tests were designed to disclose is the relation between the transmitting instrument deflection and the beat frequency. And especially, the extent to which this relation shall accurately be maintained over long periods of time. The performance of the apparatus in this respect has proved very satisfactory. The fact that both the beat oscillators are operated from the same plate and filament supplies seems largely to be responsible for this result. Thus, variations in these sources tend to produce more or less equivalent changes in both oscillators

and, therefore, affect to a minimum extent the beat frequency. Fig. 15 shows the effect upon the beat frequency of voltage variation of the plate and filament supplies. From these curves it can be seen that this system of telemetering may be operated from power supplies having poor voltage regulation without any serious inaccuracy from this cause being encountered.

Since the instrument used at the receiving station is a frequency meter, the reading of which is unaffected by the carrier current signal strength, it is likewise immune from any variation in amplitude due to the performance of the vacuum tube circuits incorporated in the receiver. Thus it is independent of wide variation in the voltage of the power supply from which the receiver is operated.

This installation has been in service for twenty-four hours daily for several months and has maintained a high degree of accuracy, comparable with the performance required of directly indicating instruments, throughout this period.

Conclusion

The outstanding features of the electron tube telemetering system may be summarized as follows.

1. Accuracy not affected by resistance or leakage of conductors.
2. No moving parts other than meter movements.

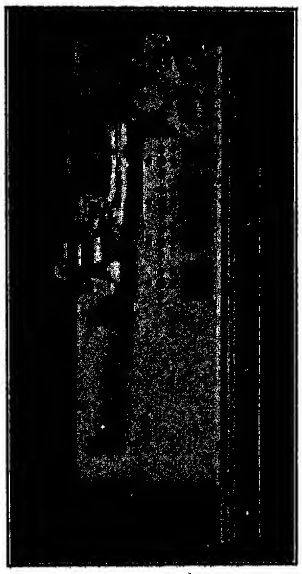

Fig. 14—Receiving Selector

3. Continuous indication given all the time. Follows all fluctuations registered by transmitting instrument.
4. Can readily be transmitted over power lines by means of carrier current or by radio. Accuracy not affected by signal strength.
5. No synchronous power required.
6. It is not limited to the telemetering of electrical quantities but may readily be applied to any deflection instrument as, for instance, steam pressure, water level, temperature, etc.
7. Does not require instruments, either for transmitting or receiving, of unconventional type. No follower mechanisms necessary.
8. It is equally suitable for the telemetering of single or multiple indications.

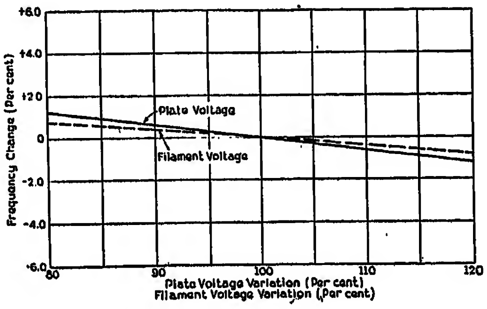

Fig. 15—Beat Oscillator Characteristics

Multiple System

a. Large number of indications given over one channel with single equipment.

b. No special synchronizing channel required.

c. Synchronism automatically established and maintained.

(Part II)

Synopsis.—*Discusses the problems of totalizing, graphic recording, and the telemetering of watthour or integrating meters. A new thyratron circuit is described, which furnishes a direct current directly proportional to the frequency at which the circuit is excited. By means of this circuit, a number of varying frequency telemetering signals may be totalized by adding together the d-c. outputs of the thyratron circuits. The resultant current is then proportional to the sum of the several frequencies.*

The use of this thyratron circuit in a field installation, furnishing totalized indications, is described.

In addition, the problem of transmitting watthour indications is generally discussed. A method of transmitting watthour readings by means of the electron tube varying frequency system is described. Signal frequencies proportional to individual dial readings of the watthour meter, are sent out. The advantages of this method are, that, by sending out individual dial readings, high accuracy is obtained; and when the dial reading of a watthour meter is transmitted, the telemetering channel is not required except when the readings are actually being observed.

Introduction

In the first part of this paper the author described the general principles of an electron tube telemetering system of the varying frequency type. The present section will deal with some further developments of this system showing how it is applied to the requirements of totalizing, graphic recording, and the telemetering of watthour or integrating meters.

These special requirements affect principally the means for indicating, at the receiving station, the varying frequency signal which is a function of the position of the transmitting instrument.

In the initial installation, described in Part I, standard frequency meters, having special windings suitable for the range of frequency used, were employed for this

purpose. While they were found to operate quite successfully in this installation, instruments of this type have certain limitations which become more apparent in connection with totalizing and graphic recording.

A minor disadvantage of the usual type of frequency meter is that it involves some degree of difficulty in the design of amplifiers. Instruments of this type usually operate on principles involving resonant circuits. The impedance of the instrument, therefore, tends to undergo considerable change with deflection of the moving system. It is difficult to design amplifiers which will operate effectively and accurately into a varying impedance. Moreover the engineering of such instruments is somewhat less flexible than is the case with ordinary instruments of the ammeter and voltmeter type where the range may readily be changed by suitable shunt and series resistances. It is less easy to alter the operating range of a frequency meter. Thus in a telemetering system there would be a tendency toward a lack of flexibility in respect of the frequency ranges used.

Frequency meters do not as a rule develop a very high torque. An instrument of such volt-ampere consumption as may conveniently be furnished by an amplifier would not be suitable for directly driving the pen of a graphic recorder. The better known types of graphic frequency meter employ some form of motor operated follower mechanism for operating the pen.

Totalizing instruments of the ammeter and wattmeter type are well known. What is required for furnishing totalized indications with a varying frequency telemetering system is an instrument or its equivalent which will give a reading proportional to the sum of a number of different frequencies.

On looking further into this problem, it is found that no immediate means appear to be available for making a frequency meter which will totalize in this manner. The reason for this is that while ammeters and wattmeters are instruments which furnish a torque proportional to the electrical quantity which they are intended to measure, all known types of frequency meters operate on a different principle. No frequency meter is known which furnishes a torque proportional to frequency. Direct reading frequency meters of the pointer, as distinct from reed, type instruments, are what is called "position" instruments rather than "torque" devices. That is to say, they do not generate a torque in opposition to a control spring. Often they have no control spring. These instruments assume a position on the scale at which no force acts upon the moving elements, which position is an indication of the frequency.

Thus the only apparent method of totalizing the readings of such instruments would be some electromechanical scheme by means of which the position or deflection of the pointers might be summated. Or, alternatively, a system involving synchronously rotating rotors and stators. Neither of these methods appears very attractive or likely to lead to a simple and inexpensive equipment.

The totalizing of readings of "torque" type instruments is simple. Readings of current in d-c. circuits can readily be totalized by connecting the several circuits in parallel so that the total current flows through a single ammeter. Readings of instruments such as a-c. wattmeters can be as easily totalized, by mounting a plurality of meter movements on a common shaft so that the resultant torque generated is the sum of the contributing torques. In each case the deflection of the instrument is a measure of the total load. But we cannot do this with "position" type instruments such as frequency meters.

Therefore, the method of attack which suggests itself is to explore the possibility of devising an instrument or circuit by means of which frequency may be measured without the use of a "position" instrument.

Consideration of the fundamental nature of the effects which are measured by the "position" and "torque" types of instrument may be of interest. If there can be discerned any common ground between these effects, it may furnish us with a clue as to how we may set out to solve this problem. The "torque" type instrument gives a deflection proportional to the strength of the current or power which actuates it. The frequency meter indicator on the other hand is, or should be, entirely independent of the magnitude of the alternating current energy with which it is supplied. It seems difficult to reconcile these differences.

Frequency is cycles per second. That is to say, it represents the number of events, one cycle being exactly like every other cycle, which occurs in a given time. The essential feature which makes the term "frequency" significant is that all of the events are exactly similar.

Let us compare this with the action of, for example, a d-c. ammeter. This furnishes a torque proportional to a field strength, which is constant, and the current to be measured. Therefore, the torque is proportional to the current. We commonly regard a current as something which flows continuously. But, we may express a current as being the flow of so many coulombs per second in a circuit. In other words, current is the coulomb frequency. A coulomb is a definite quantity of electricity, or it is so regarded. The d-c. ammeter, then, gives a torque which is proportional to the number of events occurring in a given time, each of them being identical, and being in fact the passage of one unit of charge.

We are beginning to note some aspects of similarity between the two arrangements.

It is seen that with a "torque" type instrument, we can measure the frequency with which definite charges are allowed to pass. It is important that these charges be of uniform magnitude. We could not express current as "coulombs per second" unless all the coulombs were precisely identical. But, if we know the value of

the charge and can read the current which flows as the result of so many charges being released per second, we can determine the frequency with which they are released.

From this reasoning, it is clear that if we could arrange that each cycle of our a-c. frequency could be made to release a finite charge of electricity and if the charges so released can be caused to pass through a direct-current measuring device of the "torque" type, we shall have attained our object. A very brief search through our present resources in the way of tube circuits and devices will uncover an arrangement which will accomplish precisely what is required.

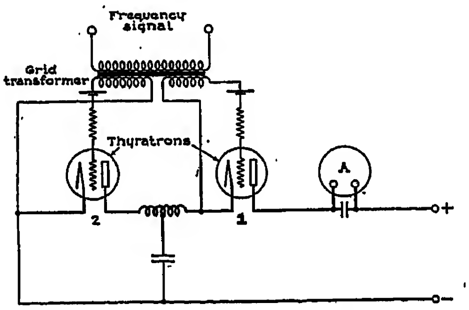

Fig. 1—Principle of Thyratron Frequency Indicating Circuit

Thyratron Frequency Indicating Circuit

The fundamental principle of this circuit is as follows. During each a-c. cycle, a condenser is first charged through a d-c. current measuring instrument, from a fixed source of d-c. voltage, and then discharged. The current read by this instrument will therefore be the product of the charge carried by the condenser and the number of times per second that this charge passes through the instrument. The charge will be the product of the condenser capacity and the d-c. supply voltage. These being fixed, the instrument will give a reading directly proportional to frequency.

Fig. 1 illustrates this principle. The circuit includes 2 three-electrode gas-filled tubes of the type known as thyratrons. It will be recalled that in this form of tube a negative voltage applied to the grid can prevent the flow of current through the tube. When the grid is made positive with reference to the cathode, current may flow, the magnitude being determined by the anode voltage and by the impedance of the circuit. Once this current has become established, however, the grid has no further controlling action. If the grid potential be again made negative, no change in the current results. If the current be reduced to zero by any other agency, for instance, if the circuit be opened at some other point, or if the circuit has such characteristics that the current which flows through the tube is a transient, and automatically ceases to flow of its own accord, then the grid resumes control and no further current can flow until the grid be again raised to a positive potential. It is this latter condition which obtains in the present circuit.

The two thyratrons are referred to as No. 1 and No. 2, respectively. The condenser is connected so as to be charged through tube No. 1 from the d-c. source. Tube No. 2 is connected across the condenser so as to form a path through which it may be discharged. The measuring instrument is arranged to read the current drawn from the d-c. source. The grids of the tubes are provided with a negative bias.

The a-c. voltage of which it is desired to indicate the frequency is connected to a grid transformer having two secondary windings. These are connected, with opposite polarity, to the grids of tube No. 1 and tube No. 2, that is to say, at any instant when a positive voltage is applied to tube No. 1, the grid of tube No. 2 is made negative, and vice versa.

Let us then assume that, at a given instance in the a-c. voltage wave, the grid of tube No. 1 goes positive. Current flows from the d-c. source into the condenser until it is fully charged up to this voltage. The current then ceases. No current can flow in tube No. 2 because the grid is at a negative potential at this instant. The constants of the circuit, that is, the value of the condenser, the value of the series resistance represented by the instrument, and the tube drop must be so selected that the charging of the condenser is completed within one-half cycle of the a-c. frequency.

Let us follow the cycle of events. Assume that about a quarter of a cycle later, the a-c. voltage passes through zero and the voltage applied to the grid of tube No. 1

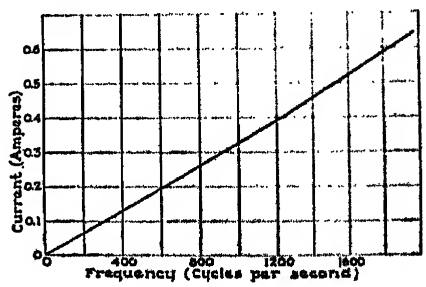

Fig. 2—Operation of Thyratron Frequency Indicating Current

as well as that applied to the grid of tube No. 2 is also zero. Current has ceased in tube No. 1. No current has been flowing in tube No. 2. Both of the tubes have a negative bias due to the bias voltage and therefore no current flows in the circuit. A quarter of a cycle later the grid of No. 1 tube will be negative and the grid of No. 2 tube will be positive. No further current, therefore, can establish itself in tube No. 1, but the condenser discharges through tube No. 2. This current ceases when the condenser is completely discharged. A quarter of a cycle later, both secondary windings of the grid transformer will be furnishing zero voltage and both grid bias voltages will apply a negative bias to both tubes. All flow of direct current from the supply ceases

until, as the cycle repeats itself, the grid of No. 1 again goes positive. The curve shown in Fig. 2 shows the linear relation between frequency and current in this circuit.

A feature of this circuit which is of interest is its flexibility in respect of frequency range. With any given instrument the relation between the current which gives full scale deflection and the frequency indicated, depends upon the value of the capacity which is used. Thus the apparatus may be adjusted to operate over any desired frequency range, within wide limits, without any change in the instrument, but merely by varying the capacity of the condenser employed.

While the operation of the form of circuit shown in Fig. 1 is more readily explained, a modification which has been developed by Mr. B. D. Bedford has superior operating characteristics. This is shown in Fig. 3. As in Fig. 1, the current flowing through the ammeter is directly proportional to the frequency applied to the thyratron grids.

The advantage of this arrangement is that the condensers are charged and discharged through a resistance but they are so connected that when one tube is charging a resistance drop is obtained which applies a negative plate voltage to the other tube. This makes it possible to operate the circuit to a higher frequency and makes it more stable if the signal is unsteady or is subject to interference.

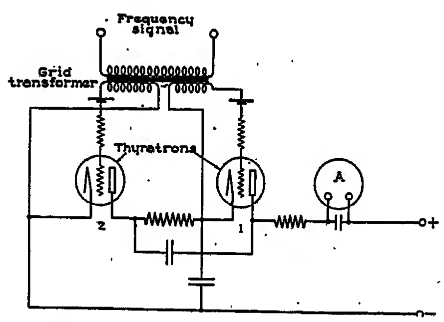

Fig. 3—Improved Frequency Indicating Circuit

It has been mentioned that if the instrument reading is to be proportional only to the frequency, the supply voltage from which the thyratrons are operated must be constant. If a source of power having sufficiently close regulation is not available the measuring instrument may be compensated so that reasonable variations in the voltage will cause no error.

Fig. 4 shows such an instrument used with the circuit shown in Fig. 3. It is of the ratio type having two windings, one of which carries the current of the thyratron circuit and the other a compensating current. The reading of the instrument being proportional to the ratio between these two currents no error is introduced if the voltage does not remain exactly constant.

Both indicating instruments and graphic recording meters of this type have been developed by Mr. St. Clair of the General Electric Company. The indicating instrument is shown in Fig. 5 and the graphic meter, which has a directly operated pen, in Fig. 6.

With this thyratron circuit any number of incoming frequencies, each a function of a meter deflection, may readily be added together merely by connecting all three thyratron circuits so that the total current flows through a common meter. Three such signals are shown totalized in this way in Fig. 7, each individual reading being given by three corresponding meters and the total being shown by a fourth instrument.

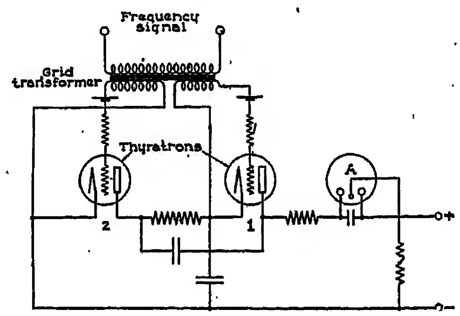

Fig. 4—Compensation for Voltage Variation

While this circuit is especially suitable for totalizing, it also presents advantages over the ordinary frequency meter even when no totalizing reading is required. It has flexibility because the frequency range may be altered without change in the meter. It permits graphic recording. Moreover the amount of power required to drive the thyratron circuit, since only grid excitation is required, is very small. Thus the thyratron circuit to a large extent takes the place of any amplifier that might be used to step up the incoming signal, whether wire line or carrier current, to the energy level required to operate a frequency meter. The thyratron circuit requires only a low plate voltage, in comparison with what is necessary when a vacuum tube amplifier is used, and is capable of much larger power output.

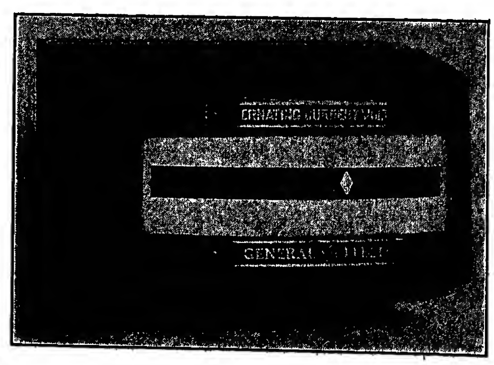

Fig. 5—Indicating Instrument

Watthour Indications

There are two principal differences between indicating and integrating instruments which affect the problem of telemetering. First, watthour metering requires a

higher order of accuracy, and, second, the constructional features of the instruments involved are different.

There are several different ways of telemetering integrating meters by means of the electron tube system. It is believed that a brief discussion of the possibilities in this connection, and of the problems involved, may be of interest.

There are two definite methods of handling the telemetering of watthour readings. One way is to transmit a signal proportional to the watts and to integrate this at the receiving end. This method has, up to the present, usually been employed. For instance, in systems operating on the frequency-impulse system impulses are sent out which are generated by the rotation of the watthour meter. These impulses are transmitted either by wire line or carrier and received at the remote station. The frequency of these impulses is a measure of the watts, at any instant. The total number of impulses is proportional to the watthours, and these may

Fig. 6—Graphic Instrument

be integrated by the usual arrangement of gear train and counter, at the receiving station.

A similar system may be used in an electron tube telemetering scheme. If we employ a rotating watthour meter at the transmitting station, we can generate a frequency proportional to the meter rotation by a variety of different means. For example we may make a simple contact device which will generate interruptions of the required frequency or we may use a beam of light and a photo-tube and holes in the meter disk.

If we use as a transmitting instrument an ordinary wattmeter we may use the standard beat oscillator controlled by means of a condenser mounted on the instrument exactly as if we were transmitting kilowatts. Either of these two schemes will emit a frequency proportional to the kilowatts.

At the receiving station, we may do either of the following. We may operate a small synchronous motor from the received frequency and drive therefrom the counter. Or we may employ the circuit shown in Fig. 1, which furnishes a d-c. current proportional to the frequency, and may cause the d-c. current to flow through a standard d-c. type ampere hour meter.

It is important to note that, if we transmit a reading proportional to the kilowatts and integrate this at the receiving station, we must have the exclusive use of the carrier current or other channel by means of which the signal is transmitted. And if this channel be inter-

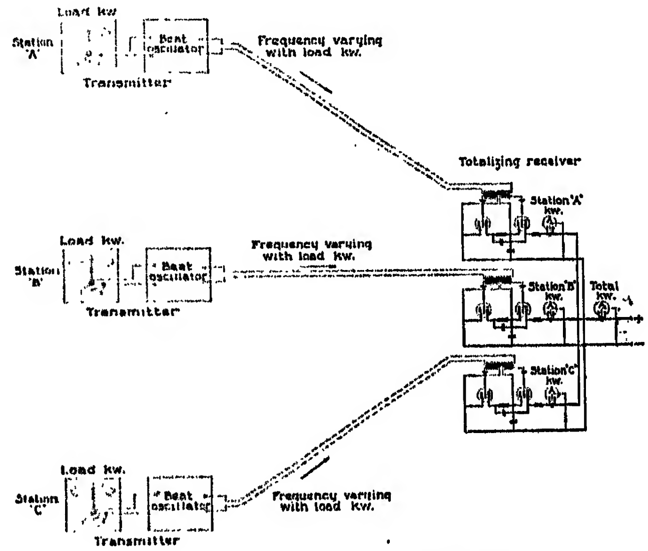

Fig. 7—Totalizing Connections

rupted, due to a system outage or other emergency, the integrated reading will be in error by an amount equal to the energy registered by the meter transmitted during the period of the outage.

Thus for carrier-current applications it may be desirable to transmit, instead of a signal proportional to the kilowatts integrated at the receiving station, a frequency proportional to the kilowatt hours already integrated at the transmitting end.

It has been pointed out that this electron tube telemetering system is essentially a deflection translating

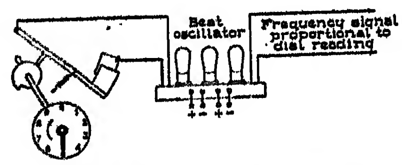

Fig. 8—Principle of Watthour Meter Transmission

device which is capable of transmitting the position of any kind of instrument. A watthour meter consists of a rotating meter element driving by means of an integrating train of gears, a number of dials which read units, tens, hundreds, and thousands or other suitable denominations. Thus if we may transmit by means of the telemetering system the position of each of the dial pointers we can make available at the receiving station a facsimile indication of the readings of all of the dials.

All that we have to do is to provide any suitable contrivance by means of which a condenser, of the same

value as would be attached to the movement of an indicating instrument for the purpose of telemetering its reading, is caused to vary its capacity in accordance with the indication of the pointer. We cannot mount a condenser directly on the pointer since this makes a complete revolution and we require that the capacity be a minimum when the pointer is indicating between zero and one and a maximum when it is between 9 and zero. But we can do this by means of a cam as shown in Fig. 8 or by any other suitable scheme.

With such an arrangement two features of special interest will be noted. First, any desired order of accuracy may be obtained as this depends entirely on the denomination of the dial which reads the lowest unit and which, therefore, moves the fastest. Clearly by reading each digit separately we shall obtain much greater accuracy than could possibly be furnished by any means embracing the complete reading in a single signal, assuming any given limits of accuracy in the telemetering system as such.

Second, with such a scheme we do not require the exclusive use of the telemetering channel. We only require to occupy it during the period when the readings are actually being observed. We shall not in general require to read an integrating meter at very frequent intervals. If we employ a supervisory system and only connect the watthour meter to the telemetering system when required, one dial at a time, the telemetering channel will be available at all other times for reading other instruments. It follows also that we shall experience no errors due to line interruptions as the integrated reading whenever it is transmitted and received shows the dial reading at that time. In a continuous automatic multiple telemetering system, of the type described in Part I of this paper, any number of watthour meter dials may be included in the complete series of indications along with wattmeters, voltmeters, ammeters, and any other indicating instruments which it may be desired to telemeter.

At the receiving end, the dial pointer positions may be shown by frequency indicating instruments exactly similar to those used for indicating any other telemetering signals and having their scales graduated from zero to ten, to one hundred, and so forth. Since, however, conventional practise in reading deflection instruments and circular dials is different, it is possible, depending upon the skill of the personnel involved, that it might be desirable in some cases to furnish the standard frequency indicating instrument movement with suitable gearing so as to give a circular dial reading.

Field Installation

In order to obtain field experience relating to the thyratron totalizing type receiving circuit, arrangements were made for further field tests on the installation described in Part I. For this purpose two thyratron frequency indicating circuits were substituted for the original vacuum tube amplifiers. One of these indicates the signal from Amsterdam and the other from Glenville. Arrangements were made for operating the system in two different ways for these tests.

According to the first set-up, the system was arranged to operate, with the thyratron frequency circuits, with the multiple selector system described in Part I. The same three readings from Amsterdam and from Glenville were provided by means of d-c. ratio instruments instead of the frequency meters used in the original installation.

By means of change-over switches arrangement was made to cut out the multiple system and to receive instead a single indication, continuously, on each carrier channel. The selectors at Amsterdam and Glenville were likewise cut out and a single transmitting instrument at each station connected to the transmitter. The two incoming signals are each indicated, continuously, by separate instruments. In addition the two signals are totalized and the combined reading is recorded by means of a graphic instrument of the d-c. ratio type.

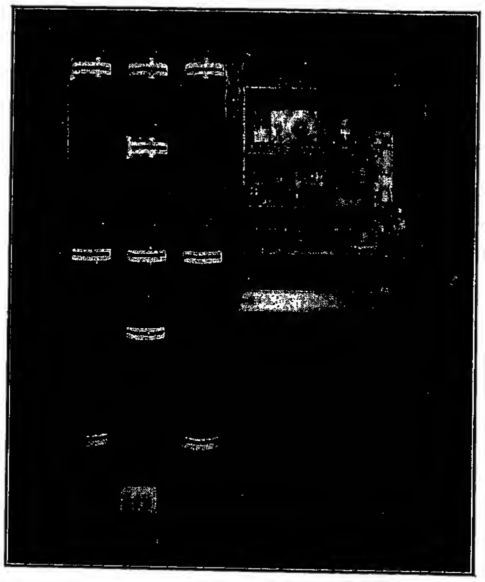

Fig. 9—View of Modified Receiving Installation

Fig. 9 is a view of the modified receiving installation. In addition to the circuit changes the general arrangement of the apparatus has been altered. All the instruments are mounted upon a separate panel such as might be installed in a load dispatcher's office. This may be seen on the right of Fig. 9.

On the meter panel the three readings from Amsterdam and the frequency check meter are on the upper portion. Immediately below are the four similar instruments which give the readings from Glenville. At the bottom of this panel are the instruments which are used when the equipment is used for totalizing.

To the right of the meter panel are the two tube equipments. The upper one contains all carrier-current and telemetering tubes, relays, and circuits, operating on the Amsterdam channel. Below is a similar unit which receives the signals from Glenville.

Discussion

E. J. Rutan: When Mr. Fitzgerald first described briefly his electron tube telemetering system in the paper presented at the Winter Convention in 1929, it was felt he had developed a system having considerable possibilities. Since that time, he apparently has had an opportunity to improve the system, and obtain operating data from an actual installation.

In the paper presented here, he has given us some of these details, together with a discussion of some of the difficulties and his methods of overcoming them. Reading the paper from the standpoint of a user of such equipment, there are several points on which more data than have been given in the paper would be desired.

In any system of measurement, especially a telemetering system, it is necessary to have detailed data in regard to accuracy. It seems in the development of telemetering systems so many schemes have been proposed that it is difficult to judge the suitability and reliability unless the accuracy performance is known. In fact, many systems proposed for telemetering do not deserve any consideration whatsoever because the accuracy is so poor compared with the well developed existing systems. Although Mr. Fitzgerald's paper gives details, and in places is extremely frank in acknowledging certain difficulties which he encountered, it is felt that his statements under the caption "Operating Characteristics" in Part I of the paper could be made more specific. It is to the paragraphs in this section that I feel the operating men will look in order to judge the quality of the scheme proposed. I am sure that Mr. Fitzgerald has the data from the trial installation which he made which would enable him to give us the accuracy with which he can transmit indications of voltage, current and power. He states that the performance was very satisfactory. This could be made much more specific.

As has been indicated in the paper, one of the important factors in determining the accuracy of the system is the constancy of the oscillating circuits at the transmitting end, for any variation in these circuits will be multiplied 10,000 to 20,000 times in the beat frequency, and affect the accuracy of the indication to the same extent. From the trial installation, he, no doubt, could read directly this effect on the indicator which he used to determine whether his system was functioning correctly. He could advise us what percentage variation he obtained on this indicator during the period of his test.

In considering the installation of the telemetering system, it is also desirable to have data on the maintenance required. From the trial installation, Mr. Fitzgerlad could probably give us some data in regard to the type of maintenance which this system required. In the event that tubes may need replacement, is it possible to substitute a new one without any change in accuracy? What frequency of inspection for the selecting device is necessary in order to obtain satisfactory operation? These questions are raised because very often the maintenance costs for the installation will greatly influence the selection of the type of telemetering system to be used.

An advantage of this system is that the receiving instruments retain their position when they are denergized, but this may become a disadvantage in the event of failure of some part of the system. No indication will be given to the operator because the instruments will hold their last indicated position. I wonder if Mr. Fitzgerald experienced any of this difficulty during his tests, and what steps were taken to provide some signal indicating that the system was faulty?

In the conclusions of Part I of the paper, certain statements are made concerning the outstanding features of this system which are, perhaps, a little too broad. They seem to imply that other telemetering systems do not have similar advantages. These will be taken up individually.

He stated that this system has no moving parts other than the meter movements. This same characteristic applies to most of the successful telemetering systems now in use.

He also states that this does not require instruments of an unconventional type. The transmitting instrument which he shows in Fig. 3 is considerably different from the standard switchboard instrument.

The advantages claimed for the multiple system in general are also available in a number of the successful telemetering systems now in operation.

In regard to Part II of the paper, many interesting adaptions of the system have been indicated, but without indicating that they have been put into actual operation, except in the case of one type of installation. Here again the accuracy data are incomplete.

W. B. Kouwenhoven: For a number of years I have been interested in the reading of watthour meters at a distance and Mr. Fitzgerald's vacuum tube scheme brings nearer the day when the Public Utility may dispense with its meter readers.

Mr. Fitzgerald, however, presents very little experimental data in his paper and there is a number of questions upon which additional information would be helpful. Among these are:

1. In the installation described in the paper, what range of frequency is used in the oscillating circuit of which the capacitor attached to the instrument pointer forms a part and what is the range of frequencies transmitted to the receiving station?

2. Is the telemetering device described simply an indicator or does it give the distant reading with precision? Data comparing the scale reading of the frequency meter for both increasing and decreasing deflections of the master meter would be of interest.

3. A full description of the variable 0.0005 μf. capacitor attached to the instrument pointer would be of value and interest. I should also like to know the dielectric that is used in its construction and to what extent do temperature variations affect its capacitance?

4. In applying this method to a watthour meter Mr. Fitzgerald shows it for a single dial only. In case the method was provided for reading each of the four dials commonly used would it be necessary to use the selector equipment mentioned?

5. Is this method limited in its operation by the type of equipment, such as transformers, voltage regulators, etc., included in the circuit between the transmitting and receiving stations?

6. What effect does the presence of harmonics in the circuit have upon the accuracy of the equipment?

C. Lichtenberg: Telemetering forms one more element in the chain of automatization. It permits essential electrical indications and measurements to be automatically transmitted hundreds of miles using conventional communication circuits. The more recent developments have reduced or almost entirely eliminated the errors due to the size and length of the lines connecting the transmitters and receivers. They have also increased the number of readings which may be automatically and continuously sent over one pair of connecting lines from one to twenty.

The systems described by Mr. Fitzgerald may be used on wire channels, carrier channels or radio channels. Each of course, has its field and limitations at the present time. The limits are of at least two kinds. These are cost and comprehensiveness.

The cost is quite definite. It can be readily determined for each set of conditions. It consists of the cost of the terminal apparatus and of the connecting lines. The cost of the terminal apparatus varies only with the type and number of indications to be sent and received while the cost of the connecting lines depends primarily on the distance between transmitting and receiving points.

If the distance is less than fifty miles and the number of readings to be transmitted is two or three, then wire lines in conventional communication channels will be found least expensive. If the distances are greater, then carrier channels may be found more expedient. Radio channels, however, do not seem at

present suited, since they require too much manual attention to permit of their economic use. It is believed, however, that radio developments may soon reach a point where its channels may prove to be valuable in transmitting telemetering information.

Comprehensiveness is the second important factor. Suppose an individual located in Chicago is connected by telemetering equipment with Milwaukee, 85 miles north, South Bend, 85 miles east, and Peoria—125 miles southwest. With present day limitations of intelligence transmission, the individual at Chicago, utilizing the telemetering equipment would have difficulty in making the best use of it without further information regarding local conditions at Milwaukee, South Bend, and Peoria. He might obtain total system load readings and distribute this information, as is being done successfully at the present time in metropolitan Chicago by the Commonwealth Edison Company. However, the cost of doing this over longer distances at the present time seems out of proportion to the results obtained. Consequently, until such time as better and less expensive methods for intelligence transmission are available, it would seem as though telemetering, excepting for limited applications, is a little in advance of the art.

The field of application of telemetering, however, would be considerably broadened if it could be made available to transmit electrical measuring instrument readings over communication channels without interfering with speech communication. At the same time, it is necessary that this be done at a cost not to exceed 5 to 10 times the cost of the readings or the apparatus to obtain the readings locally. Mr. Fitzgerald's paper indicates the probability of such development which operators will no doubt welcome as another element in reducing the cost of electrical energy and extending its field of application.

R. T. Pierce: The work described in Mr. Fitzgerald's paper is a very definite contribution to the advancement of the telemetering art. The process makes use of a medium of transmission which has been recognized for some time as being ideal when the limitations of the transmitting and receiving apparatus were overcome.

I would like to review briefly an analysis made during the development of the current balance system of telemetering. It was recognized that the limitations imposed on a telemetering system hinged around the transmitting unit. We therefore considered each electrical quantity which might be used and which I will list with a discussion of each.

1. Voltage. This may be subdivided into three groups (A) That system which produces a voltage proportional to the value being read and which is duplicated by a voltmeter at the receiving end.

(B) That system which produces a voltage proportional to the value being read and which is duplicated at the receiving end by a recording potentiometer producing a balancing voltage so that no current flows in the wires between the transmitting and receiving end.

(C) That system which produces a heating effect proportional to the value being measured, measures the heat by means of thermocouples, and transmits the thermocouple voltage to the receiving end where it is measured by a recording potentiometer.

The trouble with all of these methods is that the line resistance very definitely affects the accuracy of the system. In the straight voltage method changes in line resistance have more of an effect than with either of the other two. The distance which these can transmit is limited. A constant control voltage is necessary.

2. Current. If a current is produced proportional to the value being measured it can be transmitted independent of line resistance to the receiving end. This makes quite a simple system for medium distances. The inaccuracies aside from the apparatus involved are due to line leakage. The distance is limited by the voltage allowed on the transmitting wires and the leakage error permitted. The control voltage need not be constant.

3. Watts. A wattage proportional to the value to be measured could be produced and transmitted over three wires to the receiving end. This, however, combines the errors of the voltage and current methods and is impractical.

4. Frequency. This method was used on the installation of the telemetering system on the Chicago, Milwaukee & St. Paul R. R. electrification. The apparatus used for transmission and reception was complicated and expensive. It was independent of distance and line resistance. Later several impulse methods were devised which were quite simple except in cases where indications were desired. For watthour transmission and reception the impulse method is simple and accurate.

5. Phase Angle. Under this heading we included all Selsyn motor schemes which changed a phase condition to produce the desired results. This system has a very definite application for short distances but does not apply to telemetering installations for controlling the distribution of power on large or interconnected systems. The main limitation to long distance work is the number of wires between the transmitting and receiving stations.

Mr. Fitzgerald's paper describes a system which is an added contribution to the frequency type. The expensive transmitting and receiving apparatus used on the Chicago, Milwaukee & St. Paul R. R. installation prevented this system from being more universally adopted. The impulse methods have simplified the apparatus involved and still retain the advantages of being able to transmit over unlimited distances. The electron tube or beat type is a further simplification of the impulse types and for this reason I consider it to be an important contribution to the art.

To obtain indicating or graphic readings at the receiving end with the frequency method of the impulse type it has been quite common practise to charge and discharge a condenser through a D'Arsonval meter element. Relays are used on the low frequency impulse method but with the high frequency beat method it is necessary to resort to gas valves or Thyratrons. The principle, however, is the same in both cases although the instrument design problem is simpler in the case of the higher frequency. The objection to either of these is that a constant voltage is needed to charge the condenser and the condenser has temperature errors.

A brief comparison of the various methods used most as to their suitability for different measurements will give a picture of how they fit into the art.

The first problem is the totalization of power readings. With the current and voltage methods this can easily be done by connecting the incoming circuits so the current or voltage values are added together in one meter. In the impulse method the impulses are added up and combined into one receiver. With the beat method the current charging a plurality of condensers passes through a common meter as shown on Fig. 7. Totalization therefore is no particular problem for any of these systems.

Watthour meter readings at the receiving end are obtained with the impulse method by placing a counter in the circuit to add up the impulses. Such readings can also be obtained with the current balance method. None of the voltage methods have ever attempted this to the writer's knowledge although it could probably be worked out. Transmitting from a watthour meter is outlined in a general way in Mr. Fitzgerald's paper but no mention is made of receiving readings in terms of watt-hours with any degree of accuracy. Adding the high frequency beats is more of a problem than in the case of the impulse method.

Alternating current or voltage can easily be transmitted with the current balance or voltage methods. Ampere-hour meters with commutators and contacts can be used to transmit current with the impulse method. A special high-torque induction

ammeter or voltmeter can undoubtedly be made like the wattmeter shown in Fig. 3.

Direct current amperes or volts may be transmitted easily using the current balance or voltage methods. This has not been worked out commercially to the writer's knowledge in any other system.

The position of a water level float or like measurement has been transmitted for short distances by the Selsyn motor method. Also such readings have been transmitted over long distances by the current balance method. There is also a possibility of working this out readily with the beat principle. However there is often no control voltage available at the transmitting end. This can be supplied from a battery in the current balance method where as the others require an alternating current source.

It is quite evident that the beat system as described by Mr. Fitzgerald is readily applicable to the most important readings needed in power system control and operation with the exception of watthour meter readings. It has advantages over the other methods in the flexibility with which it adapts itself to various mediums of transmission. An induction meter element as shown in Fig. 3 is required to deliver sufficient torque to handle the variable condenser. Such a condenser could not be added to standard indicating instruments without large errors which eliminates the possibility of universally applying it to all measuring problems. However it is a very definite step in the right direction and the limiting features will undoubtedly be worked out as more experience is obtained with its use.

A. S. Fitzgerald: Mr. Lichtenberg gives a very instructive survey of the present status of telemetering. He shows how the cost of the transmission channel is an important factor, and points out the advantage of employing a communication circuit, the cost of which need not entirely be borne by the telemetering service. The question of transmitting telemetering indications over communication channels without interfering with speech is therefore important and merits further investigation. Impulse systems and direct current systems can be used in this way. The transmission of readings by means of a frequency system, without interference, is probably quite feasible. It is a matter of common experience that a telephone conversation can be carried on effectively with a high order of interference noise, provided that the interference frequencies lie outside of the frequency band necessary for the transmission of intelligence. I think it is quite likely that a telemetering channel and a speech channel could be carried by the same circuit if the telemetering frequency be kept either above or below the speech frequency band.

It will be appreciated, of course, that a carrier current telemetering channel may be superimposed upon a communication circuit without any mutual interference at all. It is common knowledge that additional communication channels are furnished in this manner by the telephone and telegraph companies. It should be pointed out that this arrangement avoids the cost of the high voltage coupling equipment which is necessary in order to establish a carrier circuit over transmission lines. All that is required is a carrier current transmitter, which need only furnish a relatively low output and a carrier current detector at the receiving end.

It is regretted that Mr. Rutan and Mr. Kouwenhoven find the paper somewhat lacking in respect of performance data. I am sure, however, that they will appreciate that, in preparing a paper, it is necessary to keep in mind the question of space in the JOURNAL and to leave out a great deal that one would like to include. Thus, in the present paper it was felt better to restrict it in scope mainly to a description of how these various circuits work. As pointed out in the paper the installation described was entirely of a developmental character. Performance data on such equipment is, it is felt, of somewhat limited value to practical engineers. It will not be long, I hope, before we shall be able to have some information of the performance of a commercial installation, and this will be of much greater interest.

However, it may be of interest to discuss a little more the question of accuracy. Suppose we consider, for a moment, for what different purposes we may wish to read instruments. These are mainly, system operation and accounting.

In operating a system, we often have to take action, sometimes immediate action, as the result of what the instrument indications tell us. But whether we open a tie-line or parallel another generating unit is determined by general conditions of the system which usually do not require a high order of accuracy to ascertain. It is more important that we get the information promptly than that we use instruments of laboratory accuracy. It has been estimated that errors of as much as five per cent in a telemetering system would, for the majority of indications in which load dispatchers are interested, be acceptable in an equipment reliable and reasonable in cost.

The other purpose for which instruments are observed is for system accounting, and station economy. Energy or watthour readings are of most importance in this connection. Here it is not so necessary that the readings be obtained promptly nor is it required as a rule to obtain them very frequently. For this reason, telemetering has probably less application in this connection, on the same principle that one sends a letter instead of a telegram if one is not in a hurry. For this reason the subject of watt-hour telemetering was only touched on briefly in the paper.

However, in the case of watt-hour telemetering, accuracy is of primary importance. It is possible that I have not entirely made my meaning clear to Mr. Pierce, with regard to the question of transmission of energy readings since he suggests in his discussion that the beat system is not readily applicable to watthour meter readings. As pointed out in Part II of the paper it is one of the special features of the system of transmitting dial positions that with any given over-all accuracy of the telemetering transmitter and receiver, any desired accuracy in transmission of watt-hour readings may be obtained by transmitting an appropriately small unit of energy on the lowest reading dial.

For transmitting the readings of the several dials, any of the methods indicated in the paper for handling more than one telemetering indication may be used.

Mr. Rutan asked some specific questions about the performance of the development field installation, and the percentage variation which the frequency check instrument indicated. This instrument only had a single mark in the middle of the scale. However, during several months operation, and of course, excluding those trouble shooting periods associated with any new development, we found that this instrument was never more than two or three pointer widths off the mark. You had to stand close to the instrument to see if it was correct or not. I would say we were getting an accuracy within two or three per cent.

With regard to the question of changing tubes the answer to this is that it all depends upon the tube. Generally speaking, if you use tubes intended for broadcast receiving, you will be liable to have to check the beat frequency when you change a tube. However, for the telemetering equipment we used tubes furnished for electron tube applications and which are manufactured to closer limits, and we did not encounter any serious difficulty in this respect.

The instrument shown in Fig. 3 admittedly does look rather different from existing switchboard instruments. But the movement is that of a standard curve drawing instrument. As a matter of fact this has an enormously greater torque than is required to carry a condenser of 0.0005 μf. Mr. Pierce may be interested to know that a condenser of the desired size was successfully mounted on a standard switchboard instrument in the

laboratory. This condenser caused no serious errors in the instrument readings. However, this arrangement did not lend itself to production manufacturing and therefore the curve drawing movement was employed instead. This is a great deal larger than is actually necessary but manufacturing facilities were not available for any intermediate size.

The dielectric of the condenser, as can be seen in Fig. 3, consists of air.

Perhaps Mr. Rutan has not quite grasped my intended meaning in the concluding summary. He says, for instance, that the advantages claimed for the multiple system are also available in a number of existing telemetering systems. But are they multiple systems? Will they transmit a large number of indications over a single channel?

The beat oscillators each operated at a frequency around 20 kilocycles and the maximum beat frequency was approximately 1500 cycles.

Mr. Kouwenhoven's questions five and six refer to the channel by means of which the telemetering signal is transmitted. As described in the paper, this may be carrier current, wire line, telephone lines, etc. It is presumed Mr. Kouwenhoven's questions apply to carrier current. The limitations applying to the transmission of telemetering signals over a carrier current channel do not differ from the conditions applying to carrier current telephones or carrier current systems in general. Harmonics in the power system, voltage or current would have no effect upon a carrier current system. It is conceivable that in cases where the beat frequency is transmitted by a conducting circuit, harmonics might cause trouble; if due to inductive interference they could get into the telemetering circuits.

Development of a Two-Wire Supervisory Control System
with Remote Metering

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Synopsis.—This paper describes the conditions leading up to the development of the two-wire supervisory control system. It enumerates the outstanding requirements of supervisory control systems in general and indicates a number of the advantages of the two-wire system. It provides a brief description of the operation of the system.

THE first installation of supervisory control equipment on a commercial basis was made on the system of the Cleveland Railways Company approximately seven years ago. This installation is still operating in a highly satisfactory manner and has been added to from time to time, so that it still ranks among the larger installations of this nature.

From this beginning, there has come into existence a number of different forms and types of apparatus which may be included under the general classification of supervisory control equipment. An intimate association with the development of a large number of these systems has made possible a thorough study of the requirements as outlined by operating companies throughout this and other countries.

In the search for a suitable type of apparatus which would be both compact and reliable, recourse was had to the products of the telephone manufacturing companies engaged in the design and construction of automatic telephone exchanges and similiar equipment. Here it was found possible to obtain relays having satisfactory characteristics which were compact and at the same time of sturdy construction. There were also available various types of selector switches which were equipped with step-by-step mechanisms which could be used for transmitting and receiving trains of impulses.

Shortly after the first installation of supervisory control equipment for the Cleveland Railways Company, it was decided that an investigation should be undertaken to determine the possibility of simplification and reduction in space requirements. The suitability of a system of supervisory control which would operate through the medium of telegraphic signal codes transmitted from one station to the other was also considered. Codes of a similar nature are widely used in the automatic telephone industry.

It should be noted that the situation in connection with the remote control of power equipment is somewhat different from that encountered in the selection of the proper number in a telephone exchange. Being connected to the wrong party is disagreeable for all of us; but it is quite evident that this condition is not nearly so serious in connection with communications as would be the case if we were to operate the wrong circuit breaker in a power station. Obviously, there must be some means of insuring the reception of the correct signal at the remote station.

To meet these requirements, there was developed the code visual type of equipment, which was originally known as the "switch" type to differentiate it from the "all-relay" type previously developed.

The code visual supervisory control equipment was designed and manufactured with the rotary type selector switch as a nucleus. Inasmuch as the particular type of switch selected for use was equipped with 25 steps, or contacts, a series of impulses totaling 25 was considered to be the most suitable for the application.

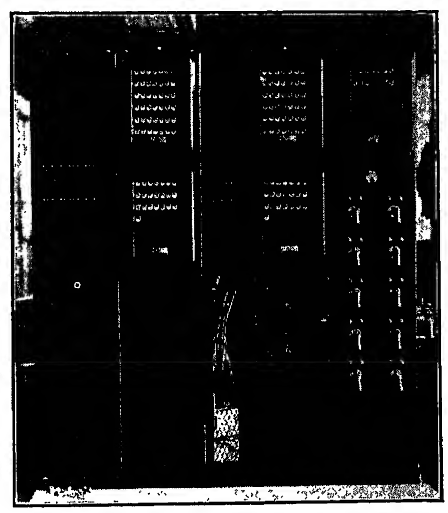

Fig. 1—View of Control Panels

The equipment was so designed that this series of impulses consisted of 22 short impulses or dots, and three long impulses or dashes. The first two long impulses might be included in the series at any point, but the last long impulse must always be the 25th in a correct series of impulses. Thus, if the 25th impulse of any series were not a long impulse, the final circuit could not be completed to cause an operation.

The code visual type supervisory control equipment in its commercial form required three wires between the dispatching office and the substation. These consisted of a common wire, a control wire and a supervision wire. By means of circuits well known to the telegraphic art,

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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the code visual equipment could be operated over two line wires between the dispatching office and the substation; but such an arrangement was not considered commercially feasible because it required frequent attention and delicate adjustment.

In order to provide the most reliable check upon the correctness of the signal received, it was determined that the most satisfactory system would be one making use entirely of relays.

Considerable interest was also expressed in the possibility of reducing the line wire requirements from three wires to two wires, particularly by those operating companies who lease their communication circuits from the local telephone company. Inasmuch as the communication circuits are leased on the basis of so many dollars per circuit mile, it is evident that a system requiring three wires will represent twice the expense in line wires that a system requiring two wires will, since it is necessary to lease four wires, even though only three are required.

It may be of interest to indulge in a little simple arithmetic to illustrate the financial advantage of a supervisory control system requiring only two wires over a similar system requiring three or four wires. The average cost per circuit mile for leased wire circuits obtained from the telephone companies in various parts of the country is approximately $42.00 per year. Assuming a nominal distance of five miles between the substations, the yearly cost for a single circuit would be $210.00. Now considering a 12 per cent return upon the capital investment to be a fair average, the expense for a two-wire line will represent a capital investment of $1750.00. Obviously, if three wires are required, it will be necessary to lease two circuits, thus doubling the expense and representing a capital investment of $3500.00. From this it is evident assuming the two systems are equivalent in other respects that the operating company can well afford to expend something more for a supervisory control equipment which requires only a single circuit rather than two circuits between the dispatching office and the substation.

There are a number of other requirements which have been found desirable by various operating companies during the course of development of supervisory control. These have been given careful consideration in the design of the two-wire system.

An ideal system of supervisory control should have the following characteristics:

1. The equipment must be simple in construction and operation.

2. It should occupy the minimum amount of space consistent with satisfactory operation.

3. It must be flexible in design so that the control key units may be mounted upon a desk or a panel. The units may be arranged in groups or as a part of a miniature bus layout.

4. It must present a neat appearance and be suitable for installation in line with the usual form of power station switchboard.

5. It should require the minimum number of line wires between the dispatching office and substation consistent with reliable operation.

6. It should require a minimum amount of attention and maintenance at regular intervals.

7. It should be protected from damage due to excessive voltages on the supervisory control lines between stations.

8. It should not be possible to obtain any false operation of apparatus units due to unusual conditions in the supervisory control equipment itself, or upon the control wires between stations.

9. It should be possible to obtain selective remote metering indications without requiring extra wires.

A study of the general trend of the specified requirements will indicate that the latest development in the field which is known as the "visicode" system approaches most nearly the ideal supervisory control system.

This design, operating over two line wires, utilizes the same type of telephone relays which has been used

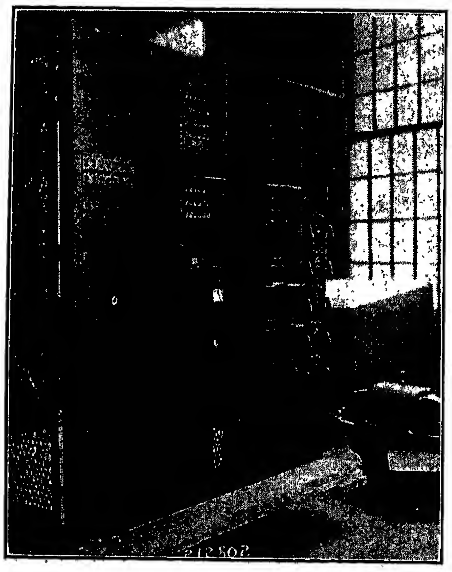

Fig. 2—Arrangement of Control Board

since the entrance of supervisory control systems into the commercial field. These same relays have been used in automatic telephone exchanges for approximately a quarter of a century. The relays are all of standard construction and are given a definite factory adjustment which requires no change under service conditions, inasmuch as they are given a thorough test and inspection at the factory before shipment.

The visicode supervisory control equipment consists essentially of a dispatching office unit, with its associated control escutcheons, and a substation unit, with its associated interposing relays and signaling equipment. The dispatching office unit and the substation unit are similar in construction and in design of the fundamental circuits. Each unit is composed of transmitting relays, receiving relays, and line transfer relays, together with the required in-

dividual point relays, according to the size of equipment.

The transmitting relays are composed of a relay chain which actually provides the means of sending out the impulses, and a series of selection relays to determine what particular portion of the code is to be transmitted by the relay chain. The receiving relays may be divided into the group receiving relays, the unit receiving relays and the operation control receiving relays. The line transfer relays consist of those relays which provide for the transfer of the line connections from the transmitting relays to the receiving relays, and vice versa, at the proper time in the operation of the equipment.

In controlling an apparatus unit at the distant station, the first operation at the dispatching office is the energizing of an individual point relay by depressing the control key at the bottom of the proper escutcheon. This in turn causes the operation of the local line transfer relays in such a manner as to interrupt the line circuit, thus releasing the apparatus at the local station and at the remote station from the normal position of rest.

At the local station, the interruption of the line circuit causes the equipment to be prepared for the transmission of the first series of impulses. These impulses cannot be transmitted, however, until the line circuit has been completed at the remote station. At the remote station, the interruption of the line circuit causes the equipment to operate in such a manner as to connect the first set of receiving relays to the line circuit in preparation for receiving the first series of impulses.

After the transmission of this series of impulses, the line transfer relays at the local point disconnect the transmitting relays and connects the first set of receiving relays at this station. Simultaneously, the line transfer relays at the remote station operate in such a manner as to disconnect the first set of receiving relays from the line between stations and connect the transmitting relays in such a manner as to transmit the first series of impulses from this station as soon as the receiving circuit has been set up at the local station.

At the conclusion of the first series of checking impulses, the line transfer relays at the remote station operate in such a manner as to disconnect the transmitting relays and to connect the second series of receiving relays. At the same time, the line transfer relays at the local station act in such a manner as to disconnect the first series of receiving relays and to connect the transmitting relays preparatory to transmitting the second series of impulses from this station. This series of impulses is sent out as soon as the receiving circuit at the remote station is prepared to receive it.

The completion of the second series of impulses transmitted from the local station causes the line transfer relays to operate, disconnecting the transmitting relays and connecting to the line circuit the second set of receiving relays. The line transfer relays at the remote station also operate to disconnect the second set of receiving relays and to connect the transmitting relays preparatory to sending out the second series of impulses from this station.

Upon the completion of the series of checking impulses from the remote station, the line transfer relays at that station disconnect the transmitting relays and connect the operation control receiving relays to the line. At the local station, the line transfer relays disconnect the second set of receiving relays from the line and connect the transmitting relays to the line preparatory to sending out the operation control impulses.

At the local station, the completion of the third series of impulses permits the line transfer relays to disconnect the transmitting relays and connect the third set of receiving relays which correspond to the operation control receiving relays at the distant station.

The line transfer relays at the remote station disconnect the operation control receiving relays from the line, at the same time causing the operation of the apparatus unit and connecting the transmitting relays to the line preparatory to transmitting the third series of im-

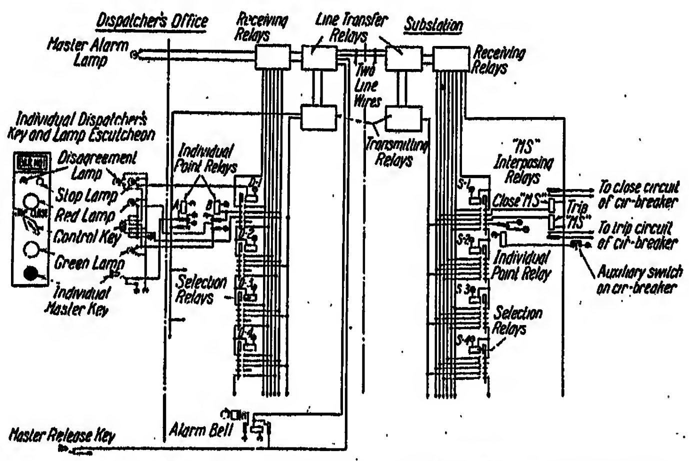

Fig. 3—Schematic Diagram of Fundamental Principles of Operation

pulses as soon as the apparatus unit has changed position.

When the third series of impulses or indication code has been transmitted from the remote station to the local station, thus indicating that the apparatus unit has actually changed position, the line transfer relays at both stations are actuated in such a manner as to disconnect both transmitting and receiving relays from the line and restore the equipment at each station to its normal condition.

In case the operations were originated at the remote station, the functioning of the equipment would be the same as that described above, except that in this case, the remote station would be the first to transmit a series of impulses. Furthermore, at the conclusion of the third series of impulses transmitted from the remote station to the local station, the equipment at the remote station would be prepared to receive the third series of impulses from the local station and the local station would be prepared to transmit the third series of im-

pulses, only when the proper circuit is set up by the operator at the local station.

After this circuit is completed by the operator at the local station, the third series of impulses is transmitted from the local station to the remote station if desired, thus causing the operation to take place, after which the third series of impulses is again transmitted from the remote station to the local station, thus indicating the change of position of the apparatus unit.

In case the operator at the local station did not desire to cause an operation of the apparatus unit at the remote station, the equipment at both stations could be restored to normal by depressing the release key. This same release key may be used at any time during the cycle in order to cancel an operation which has been started but is not to be completed. Release is instantaneous with the pressing of the key.

Practically any operation can be performed by means of the visicode supervisory control equipment which does not require the simultaneous use of more than two wires between the local station and the remote station. We may close and trip a circuit breaker or similar switching device, raise and lower the voltage of a generator by means of a motor-operated field rheostat, control the operation of a voltage regulator, control the gate opening on a waterwheel generator, and many other similar functions. We may also give the indications associated with these various control operations, and in addition, we may indicate water level and approximate load upon a machine by means of step-by-step indication.

Current-balance remote metering may be used in conjunction with the visicode supervisory control equipment, operating over the same pair of wires between the local station and the remote station. It is evident that the metering indications will necessarily be obtained selectively and that the operation of an apparatus unit cannot be obtained at the same time as a metering indication. However, an automatic operation which may have occurred during this time will be indicated immediately upon the release of the metering circuit. Furthermore, a change in position will be indicated even though the apparatus unit may have returned to the original position.

By means of current balance remote metering equipment, we may obtain accurate indications of current, voltage, kilowatts, and any other type of indication which may be obtained by the use of a Kelvin type of instrument.

In order to obtain a selective remote metering indication, we assign a standard point for this purpose so that whenever this particular point is selected, the line wires are connected to the remote metering circuit and are disconnected from the transmitting and receiving relays at each station. In order to release the remote metering circuit so that other operations may be performed, the operator at the local station depresses the release key, thus opening the line circuit and causing the supervisory control equipment at both stations to be restored to the normal condition.

Discussion

J. E. Goodale: The New York & Queens Electric Light & Power Company is operating three substations over supervisory control equipment and has had experience with this equipment for several years. The two later stations are of 30,000-kv-a. capacity each and the supervisory control consists of relay equipment similar to that described in the paper, although a larger number of wires is used. A careful record of operation of the supervisory control systems for the year 1929 showed for the two stations a total of approximately 124,000 operations of which 13 were incorrect and in most cases the cause of the incorrect operations has, we believe, been corrected.

We believe that there are some things which it may be necessary to do in operating a substation which cannot be accomplished over a two-wire supervisory system. We have found it desirable, for example, to operate our induction regulators over the supervisory system from the control station, and while this operation is being performed to read the voltage on the lines being regulated. So far as we can see this could not be accomplished with the two-wire system. The same reasoning would, of course, be applied to synchronizing, because two simultaneous readings would be required for this. With the system which we now have, if the supervisory chain should for any reason get out of step and stop at any point, we can reset the equipment at the starting point. With a two-wire system it seems that this cannot be accomplished unless an additional wire is added.

There is, of course, a saving in cutting down the number of control wires. On our own system, owing to the importance of the load supplies by the supervised substations, we have installed our own control wires. The control cable used consists of 10 pairs of No. 18 paper-insulated wires in a lead sheath. We have had at least one case where the control cable to one of the substations was burned apart by a manhole fire, but no incorrect operation or indication resulted. Consideration is being given to equipping our particular substations with two sets of control wires over different routes. This procedure, if adopted, would make a smaller number of wires used for control very desirable, particularly if the control wires were leased from the telephone company.

As I understand the system of supervisory control described in the paper, a transfer relay operating at each point is required. It would be interesting to know how this feature affects the speed of the equipment compared to the equipment now in use. In the three-wire supervisory system the equipment can be divided into individual groups, but so far as I can tell from the paper this is not the case with the two-wire equipment. In case of trouble with the supervisory equipment, it would seem to be less difficult to locate what was wrong if the system could be divided into groups, particularly if the system were a large one.

Fig. 3 shows an individual point relay connected to the auxiliary switch of the oil circuit breaker. We have found that supervision of the trip coil and its connections is desirable. If a relay were directly in series with the trip coil, it would eliminate this individual point relay, obtain trip coil supervision and give a correct indication regardless of the position of the breaker. The scheme shown in the paper would indicate that the oil switch was in the closed position if the breaker happened to be of the truck type and were pulled out into the aisle.

Anyone intending to install and operate one of the supervisory systems described by the paper would be interested in:

First: Whether or not the supervisory system described is trip free or whether the trip-free feature is to be obtained by the use of external relays;

Second: Whether or not it is desirable to have a panel in the supervised station for the remote control and supervision of the oil circuit breakers, this panel to be exactly similar to the one that is installed in the dispatcher's office. It would seem

that the switch layout and panel should be a one-line diagram of the station;

Third: What is the best method of obtaining the direct current for the operation of the supervisory control, and is it desirable or necessary to keep it separate from the station batteries at both the dispatcher's station and the substation?

C. A. Mayo: I find in making a comparison of costs and using the figures in Mr. Wensley's paper of $42.00 per year per circuit-mile for leased wires which for four wires represents a capital investment of $3500.00, our capital investment for an equivalent 5 miles is $3150.00 which is somewhat less. Not only is the investment less but we have available 28 conductors for use in other ways such as, private telephone lines, voltage indication of regulated circuits and the control of R. O. series circuits along the cable route.

Our first installation was in 1922 and I believe was one of the first, if not the first of this type of system to go into operation with both control and indication. As with any other new piece of equipment we had our difficulties, but these were soon cleared up. At first we tried to operate with the ground for the common return, but due to excessive stray ground currents this had to be abandoned, and substituted by a wire in the control cable.

In the beginning false operations and indications did occur but soon after the first installation the possibility of false operation was practically eliminated. At present the system fulfills the requirements and is entirely satisfactory. Our second installation took place in 1923 and the other three followed, the last being installed in 1928.

I think the comparison of costs of an attended substation as against the unattended substation with supervisory control is worthy of note. We figure that an attended substation would cost us approximately $5500.00 per year while the unattended substation with supervisory control costs us approximately $2000.00 per year. This last figure includes carrying charges on the investment, maintenance, repairs and janitor service for the station. This shows a considerable saving and is much more satisfactory.

The development of a two-wire supervisory control system is certainly a step in the right direction since it means a reduction in the cost of both installation and operation.

In conclusion I would just like to add that I feel there are many installations for some type of supervisory control which could be justified from an investment standpoint and would be entirely satisfactory.

Centralized Control of System Operation

BY JAMES T. LAWSON*

Member, A. I. E. E.

Synopsis.—This paper considers the application of centralized control of system operation of the Public Service Electric and Gas Company in New Jersey. A brief history of events leading to the installation of supervisory system operation is given, with a detailed description of the apparatus and the methods used to carry out the indications, together with a statement as to what is being accomplished in improving the service.

* * * * *

IN the early days of the generation of electrical energy there was little need of load dispatchers or system operators. Then, each power station supplied its own local territory, usually at 250 or 500 volts direct current or 1000 or 2400 volts alternating current. The operating man in charge of the power station or distribution system could direct the handling of apparatus and feeders without any trouble. Power stations were not run in multiple and each one could be operated in a manner best suited to it.

Gradually, as consolidation was effected and territories enlarged, several plants were tied together, and in time, voltages were raised. The method of allowing superintendents or chief engineers to operate the distribution systems and the stations according to their own individual ideas led to confusing, inefficient operation, and had to be discontinued.

This forced in a group of men, who would be available at all hours to guard the operation of the system as a whole.

Such a scheme was first started in our system in 1900, to handle d-c. railway feeders. At this time, the operator did the work as a side line to other duties and his entire equipment consisted of a small plug board, somewhat like a cribbage board, with the names of the stations and substations lettered on the left-hand side and the feeder numbers across the top. A series of holes was drilled across the board to match. By placing pegs in the proper holes, it was possible to keep track of the railway feeder operation.

Later, this scheme was extended to follow up the operation of the a-c. system, both for railway and lighting. At this time there was no attempt at parallel operation of power stations.

In 1906 parallel operation of the stations became necessary and centralized control of system operation imperative and the first load dispatching office was then started in our Marion Station, Jersey City. The office controlled the operation of the power stations, and distribution and transmission systems, in Hudson, Bergen, Passaic, and Essex Counties, or in the Northern Division.

The operating board consisted of a wooden drawing board, an elaboration on the original plug board about 6 by 12 ft., painted white and marked with single wire diagrams of the transmission lines and station and substation busses, and showing symbolically the main apparatus in each station and substation. The diagrams of transmission lines, apparatus, and busses were placed on the board by using gummed paper cut in narrow strips, and gummed letters and numbers.

Wooden plugs, colored red and white, were used, placed in holes drilled in the board. But few private telephone lines were in use.

In 1909 and 1914, load dispatching systems were established in the Central and Southern Divisions. At this time the three divisions were not electrically connected and we thus had four load dispatching offices. The work increased rapidly, and as the system expanded and the divisions were tied together, the future seemed to point to the need of one central load dispatching office to control the operation of the entire system as a unit, not only within itself but in its relation to connections which might be effected with other companies.

Accordingly, plans were made to consolidate three of the offices and move them into a centralized office at Newark; this was accomplished in 1926.

A load dispatcher must be familiar with every operating detail, and an accurate and up-to-the-minute diagram of the bus layout of each station and substation is necessary. The load dispatcher's diagram of busses, and substation and generating station apparatus, is known as a "Pilot Board." Our first pilot boards were made of wood, using gummed paper for the diagrams and small wooden plugs inserted by hand in holes drilled in the board to show the switch and apparatus positions. These were changed to a type of board using instead of plugs, a scheme of small colored lights manually controlled by the load dispatcher from his desk. (See Fig. 1.)

These types of pilot boards are accurate only in so far as the plugs or lights are changed in response to telephone messages, or orders given or received. Therefore they are not always an accurate visual record of the system. Time is lost in waiting for each station or substation operator to report switch positions and switch movements, especially in times of stress and trouble.

A board which automatically shows the position and movement of the switches not only serves as a diagrammatic record but also enables the load dispatcher to follow the switch operations as he directs them, and, more important in times of trouble, gives him an instantaneous indication of system conditions.

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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From these indications, without waiting for reports from generating station and substation operators, he is in a position to act immediately toward restoring service and maintaining normal system conditions.

Accordingly, when it was decided to centralize the load dispatchers' office, an automatic pilot board was considered; but the cost for the entire territory was so great that it was decided to have only automatic indication from the stations and substations in the vicinity of Newark, the remainder to be manually controlled.

The location of the system operator's and load dispatcher's office is quite important; it should be as close to the records and operating department's facilities as possible. The office was therefore located in the company's main office building in Newark, N. J., convenient to every operating record and personnel facility.

The usual red and green indicating lamps are employed to show the positions of the various oil circuit

FIG. 1—MANUALLY CONTROLLED LOAD DISPATCHER'S PILOT BOARD

breakers in the generating stations, substations, and transmission system. For the substations in the Essex Division, together with the Essex, Marion, and Kearny generating stations, the Elizabeth and Bayway substations of the Central Division, Athenia switching station in the Passaic Division, and Hudson switching station in the Hudson Division, the indications are automatic, and the apparatus used to accomplish this is the distributor type of supervisory control and remote indicating equipment. There are 42 distributors in all, located in 21 substations and in Marion, Kearny, and Essex generating stations. Some of the smaller substations do not have distributors, the positions of the oil circuit breakers being indicated over direct wire connections.

Each distributor will automatically indicate from 50 to 100 switches, depending on whether or not supervisory control of the switches is desired in conjunction with automatic indication. Therefore, one distributor will usually take care of a substation while two or more are needed for the generating stations.

The positions of the oil circuit breakers in substations not equipped with automatic indicating apparatus are shown by means of small control switches, manually operated, that light red and green lamps, the information for keeping these indications correct being obtained by the load dispatcher by telephone from the substation operators.

Provision has been made for four load dispatchers' telephone positions, with an extra position for the chief load dispatcher. Each operating position has a capacity of 40 telephone lines, and in addition, a special monitor type switchboard has been provided for the chief load dispatcher with multiple connections to each of the 160 lines furnished by the four operating load dispatchers' positions. All of these lines are not in use at the present time, ample provision having been made for future growth.

The load dispatcher's office consists of two rooms. The office proper contains the remote metering panels, telephone switchboards, pilot board, etc.; the second room contains the apparatus, batteries, motor generator sets, etc., for obtaining automatic indication of the switches in the substations and power stations.

The positions of the various oil circuit breakers and disconnecting switches in the system are shown on the load dispatcher's board by means of colored lights. Red and green lights indicate the closed and open positions of oil circuit breakers, and white lights with a horizontal or vertical black line across the lamp, the closed or open positions of disconnecting switches. A group of three lights is used for an oil circuit breaker, (the red and green referred to above), and in addition, a clear white light, the function of which is to indicate that the oil circuit breaker has changed its position. This white light is extinguished by a small push-pull, single-pole double-throw switch, thus compelling the load dispatcher to acknowledge the operation of the oil circuit breaker and also giving him notice that an oil circuit breaker has operated, since under normal operation the board is operated with all white lights unlighted. In the arrangement used, the white light is on top, the red and green lights directly below in the order given. Underneath the green light, the oil circuit breaker designation is painted on the face of the board. So far as practicable, the various oil circuit breakers and disconnecting switches are shown in their correct positions relative to one another. While all oil circuit breakers in the transmission system are indicated, only such disconnecting switches as perform a switching function are shown. Disconnecting switches which serve only to isolate other apparatus from the system are not shown on the load dispatcher's board, since in most cases such isolating disconnecting switches are stick-operated, so there is no simple means of obtaining automatic indication. The load dispatcher is supplied

with simplified wiring diagrams of each station and substation, which show all such isolating switches as well as other necessary information not feasible to show on the indicating board.

This system requires two separate sources of energy at the load dispatcher's office; 125-volt, three-wire direct current is required to operate the distributor motors and the relays of the system; 24-volt direct current is required for the indicating lamps. For this latter service, a 5-kw., 24-volt motor-generator battery-charging set is used with a 24-volt storage battery floating across its terminals. This storage battery has a capacity of 60 amperes for eight hours. For the 125-volt power, two 70-volt, 1-kw. d-c. generators are driven by one motor with a 60-cell storage battery floating across the generators. This battery has a capacity of 20 amperes for eight hours. Both batteries are of the sealed-in rubber-jar type, commonly referred to as the automobile-type of storage battery, and are contained in the apparatus room. This type was selected so that it would not be necessary to construct a separate battery room. Spare battery and motor-generator equipment is provided, ready for service.

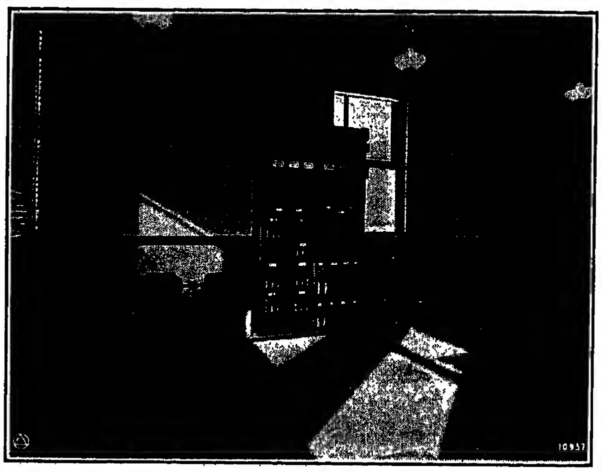

Fig. 2—Batteries, Motor-Generator Sets, and Control Panels

Each battery, with its charging set, is controlled from a separate panel, shown in Fig. 2. These panels are so constructed that on failure of a-c. power, the charging set is disconnected on both the a-c. and d-c. ends. As soon as a-c. power is available, the charging set starts automatically, and when the d-c. generators reach full voltage, a contactor closes, connecting the d-c. terminals to the bus on the back of the panel. Both motors are 220-volt, three-phase, 60-cycle squirrel-cage. The power equipment is shown in Fig. 2; from left to right are the 120-volt battery, 120-volt charging set, 120-volt panel, 24-volt charging set, and 24-volt battery.

Fig. 3 shows some of the relay and distributor cabinets. The cabinet at the left is a 100-relay cabinet, there being 50 relays on the reverse side of the cabinet. The second from the left is a combined distributor and relay cabinet. The third and fourth from the left show cabinets with a capacity of three distributors each, although the two middle distributors have been removed. These clearly demonstrate the method in which a distributor is connected to the cabinet. It illustrates also the ease with which a distributor may be taken out for inspection or repair. A later type of relay distributor is shown in Figs. 4 and 5.

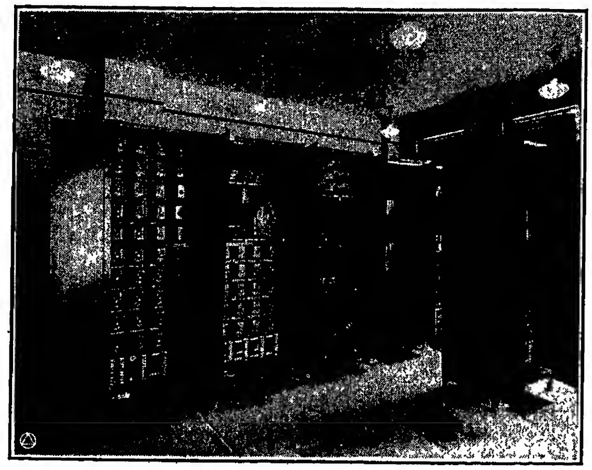

Fig. 3—Relay and Distributor Cabinets

One or more distributors are located in each power station or substation, depending on the number of switches involved. Each pair of distributors is tuned to run at exactly the same speed. They are connected by leased telephone wires, so that an indication of a switch movement on the station or substation indicator is communicated to the distributor in the load dis-

Fig. 4—Improved Relay and Distributor Panel, Front View

patcher's office and in turn to the lamps on the pilot board. Some 300 mi. of leased telephone lines are used for switch indicating purposes.

A general view of the front of the load dispatcher's board is shown in Fig. 6, and a rear view in Fig. 7. The board is constructed of ebony asbestos panels, 42 in. by 51 in. by 3/4 in., with a dull, lacquered finish. In order that changes and future installations may require only that receptacles be mounted and wired and the designations painted on the front of the board, the panels were so drilled that any arrangement of lights could be obtained without further drilling.

As shown, the panels are mounted two high, making the present size of the board 31 ft. long and 8 ft. 6 in. high. It is supported on a steel base and wood sill, raising the base of the panel 18 in. from the floor.

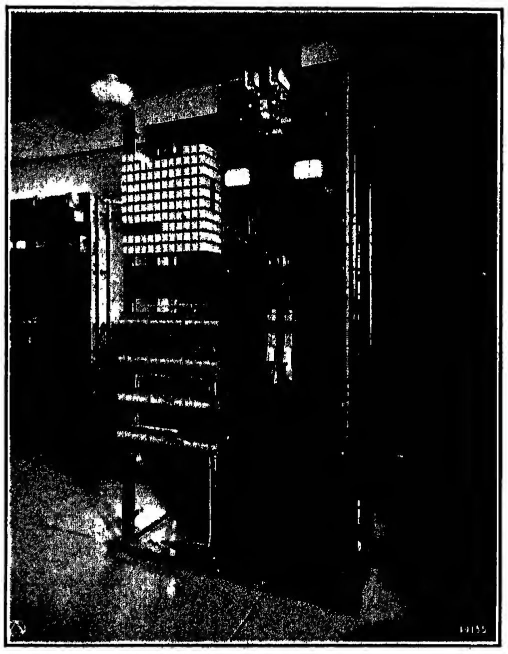

FIG. 5—IMPROVED RELAY AND DISTRIBUTION PANEL, REAR VIEW

This was necessary in order that the view of the bottom rows of lamps might not be obstructed by the special two-position, low-back telephone switchboards. Future extensions of the board will be in the nature of semicircular wings on each end, so that the ultimate size of the board can be 42 ft. long.

As shown in Fig. 6, the room is arranged for four load dispatchers and one chief load dispatcher; the chief load dispatcher's desk is shown in the foreground. The control key switches for the white "acknowledgment" lights and the manually-operated indications are in black shallow cabinets alongside the dispatchers' desks. Fig. 7 shows the rear of the load dispatcher's board. The terminal racks at the right are for making cross-connections between the cables going to the control key cabinets just mentioned and the groups of lamps. Strips of black paper have been pasted over the unused positions on the board, so that any light which may be behind the board will not mar the appearance or affect the visibility of the lamp indications.

The Public Service Electric and Gas Company

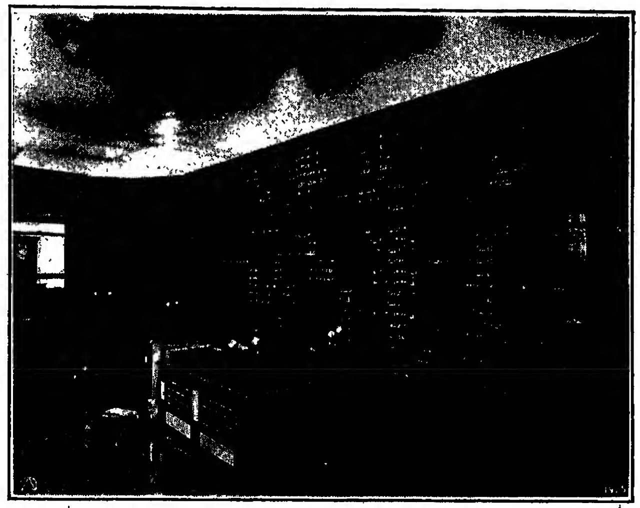

FIG. 6—LOAD DISPATCHER'S PILOT BOARD, FRONT VIEW

supplies the more populous sections of the State of New Jersey with electric light and power. That portion of the state served from the New York State line on the east to the Delaware River below Camden on the west is outlined on the map of the State of New Jersey, in Fig. 8. The territory is 110 mi. long and covers an area approximately of 1700 sq. mi. as compared with

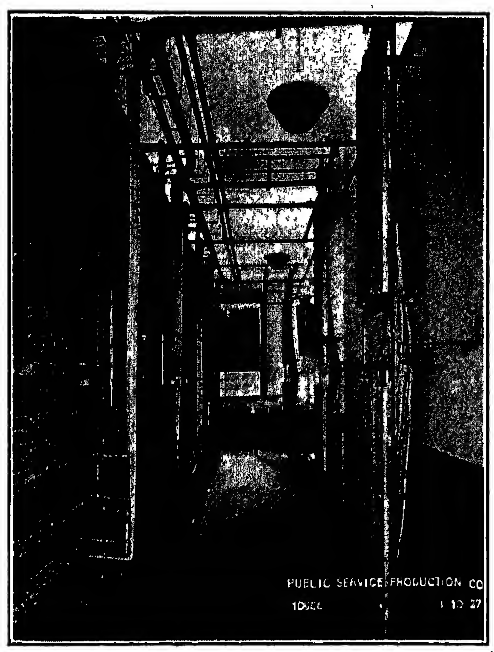

FIG. 7—LOAD DISPATCHERS' PILOT BOARD, REAR VIEW

8224 sq. mi. in the state. This area includes about 88 per cent of the population of the state, which exceeds 3,500,000; electric meters, December 31, 1929, numbered 886,797. The portion of the territory directly

supervised and operated from the Newark Terminal load dispatchers' office is shown in the clear area. The stations and substations which have automatic indication on the load dispatchers' board are located within or adjacent to the City of Newark. Indications from the other stations and substations are controlled by manually operated miniature switches manipulated

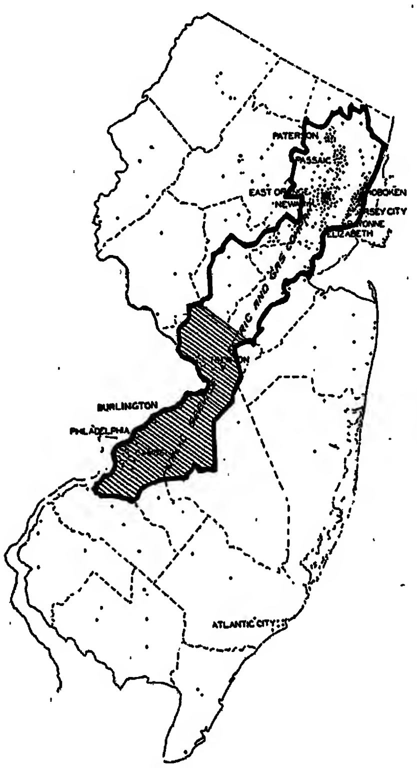

Fig. 8—Map of New Jersey showing the Territory of the Electric and Gas Company. The Unshaded Portion is Operated by Newark Load Dispatching Office

by the load dispatchers from information obtained by telephone. The territory indicated by the shaded area on the map is known as the "Southern Zone," and has no automatic indication equipment installed.

The entire Public Service territory is supervised from the Newark load dispatching center, although the southern area, or shaded portion of the map, is operated directly from a load dispatching office at Burlington.

In the entire system, there are 131 Public Service and industrial substations, nine switching stations, and five generating stations. Of this number, the Newark Load Dispatcher has direct supervision over and operates 87 substations, eight switching stations, and four generating stations, leaving 44 substations, one switching station, and one generating station in the Southern Zone.

Associated with the load dispatcher's board, and using the same equipment, supervisory control apparatus has been installed in an adjoining room to obtain complete remote supervisory control of six automatically operated unattended substations. In these six remote controlled substations, we combine the supervisory indications for load dispatching purposes with the supervisory remote control of the automatic substations.

The following table shows the number of automatic indications on the load dispatcher's board.

Station or substation	No. of indications on L. D. B.	26,400 or 13200 v. O.C.B's.	4150 v. a-c. three-phase circuits	600-volt d-c. circuits	Rotating machines
*1 Essex	209				
2 Hudson	46				
*3 Marion	174				
*4 Kearny	100				
5 Miller St.	8	8	18	10	2
6 Norfolk St.	7	7	20	9	2‡
7 Clay St.	6	6	14		
8 Montclair	5	5	15	4	2‡
9 Bloomfield	7	7	12		
10 Race St.				2	1
11 Lakeside Ave.	6				
12 Washington Ave.	7				
13 Central Ave.	6				
14 Irvington	11				
15 Waverly	6				
16 City Dock	29				
17 Harrison	9				
18 Elizabeth	11				
19 Bayway	11				
20 Plank Road	5				
†21 Federal Ship	2				
†22 Crucible Steel	3				
†23 Submarine Boat	2				
24 Athenia	81				
	751	33	79	25	7

Notes

*Generating stations—Others are substations.
†No. distributors used—Indications by direct leased wires.
‡Also two steps of field control on each motor-generator set.

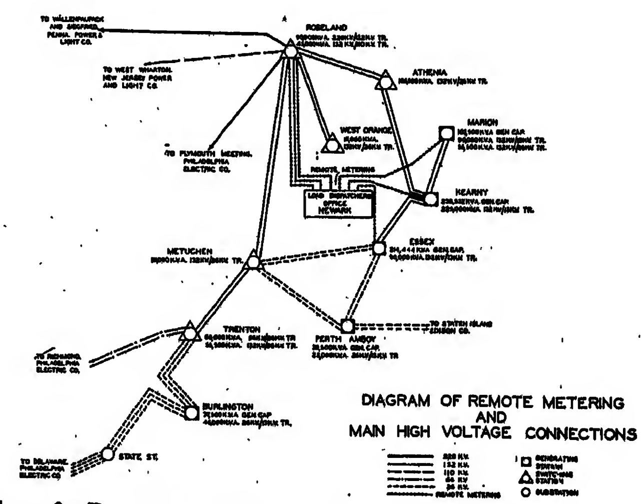

Fig. 9—Diagram showing Interconnections with Other Companies and Remote Metering Scheme

In addition to the indication board, there is certain accessory equipment to aid the load dispatcher in keeping informed at all times of the status of the system. This includes an automatic radio clock, for receiving the Arlington time signals, a master frequency clock, a graphic frequency recorder, and graphic wattmeters of the generating stations. The frequency recorder has a

scale which can be read easily to five one-hundredths of a cycle. Three of the recording wattmeters indicate, by means of remote metering, the kw. load on the generators of the three stations, Essex, Marion, and Kearny, and the fourth is a totalizing wattmeter which gives the total of the three station wattmeters. Additional space is provided for instruments of this type as future need for them may arise. Some of the future requirements along these lines are instruments to record and indicate by means of remote metering the interconnected loads supplied or purchased from other companies. Fig. 9 shows the scheme of remote metering which will record the interconnections about to go in service.

Apparatus for recording telephone conversations to and from the load dispatchers' office is installed, enabling the operators to record the actual conversations which take place.

Perhaps the most important factor in the operation of any system is the ability to maintain perfect and continuous telephone communication between the load dispatcher and every station and substation operator. To provide this, a private telephone system is maintained over leased wires having no connection with any other public service telephone exchange. By means of this system, the load dispatcher is able to keep in close touch with the entire operating personnel. Throughout the state, there are some 850 mi. of telephone wires for this purpose, all leased from the local telephone company.

To back up the private telephone wires, each station and substation has a second wire through the local public service exchange to be used in case the private wire fails. In times of emergency, the load dispatcher's calls take precedence over any other calls on these wires.

The load dispatcher's duties make it imperative that he be thoroughly informed on every condition in every part of the system. A complete set of maps and records is kept showing the routes, lengths and sizes of transmission lines and cables, and the capacity of all generating and substation apparatus.

It is difficult to estimate the value of a load dispatching system or the value of one type of load dispatching equipment over another; these, we believe, are matters of local importance and must be judged by the individual utility which may wish to employ the several methods. No doubt load dispatching can be, and is, handled with simple as well as elaborate equipment,—a matter of opinion. Our experience in using the simplest as compared with the elaborate leads us to believe that the automatic indicating equipment, backed up with accessory apparatus, gives the best results as regards safety, service, and economical handling of station load.

After an experience of three years with the automatic indication system, we have not changed our opinion.

With the completion of the 132-kv. transmission system and the existing and approaching interconnections with other companies, the advantage of centralized control of system operation to this company has become more apparent.

The 132-kv. transmission system has made it possible to schedule the loading of generating stations so as to obtain operating economy. These load schedules would be almost impossible to follow effectively if the system were not controlled at a central point.

At the end of the current year, 1930, this company will be interconnected with three other companies, and there will be operating agreements with each, governing the interchange of power. This interchange will fall into several classes and each class will be regulated by different conditions and restrictions. It is evident that centralized control will be required to procure reliable action, to take advantage of effecting economies, and to avoid penalties which might result from the lack of coordination.

During 1929, the load dispatchers issued a total of 238,986 operating orders in connection with switching changes; and of this total, only one operating mistake resulting in interruption to service is chargeable to the load dispatcher. This one interruption occurred at a time which caused no inconvenience to the customer; in fact, it was not noticed or reported. We feel justified therefore in having incurred the cost of installing and maintaining the automatic indicating system.

The author wishes to acknowledge the help in preparing this paper given by H. W. Codding, Public Service Production Company, who designed and constructed the load dispatchers' board, and W. C. Mangels, System Operator, Public Service Electric and Gas Company, both members of the Institute.

Discussion

C. A. Mayo: It seems to me that the subject of supervisory control has many applications and is becoming more popular every day. The rapid increase in substations and the daily growth of interconnections demand something of this nature to automatically centralize the control of such a system.

I would like to describe our own system which in some respects is similar to the system of the Public Service Electric and Gas Co. of New Jersey. Our system is not as expansive since we have five substations located within a radius of less than five miles of our Malden station, which is our operating center. These substations are supplying light and power to a population of approximately 250,000. Being located within five miles of Boston it is chiefly a residential area.

These substations are all automatically operated and unattended. Each has an ultimate capacity of 10,000 kv-a. By means of our supervisory system we have control and continuous indication of some 100 switches on high- and low-tension circuits also both a-c. and d-c. street circuits.

There is another feature in which we differ from the New Jersey installation and that is that we are leasing no wires from the telephone company, but have our own control cables installed. These cables are the standard 16-pair, 32-conductor paper-insulated lead-covered, as used by the telephone company.

H. W. Codding: Mr. Lawson has reviewed the history and development of the load dispatching system, including methods and equipment, as used by the Public Service Electric and Gas

Company of New Jersey. He has shown the development of the system from a small beginning to its present elaborate layout and has given the reasons for each step of the development.

There is a big step between the system at the time of the first 13-kv. lines and the present 132-kv. and 220-kv. transmission lines. The 13-kv. lines, now largely replaced by 26-kv. lines, which were considered such a great advance at the time of their first construction, are now coming to be looked upon as hardly more than distribution feeders. While at the present time the load dispatcher is still concerned with the 26-kv. lines, as well as the 132-kv. and higher voltage circuits, there is reason to believe that in a not distant future, the operator of each generating station or switching center will have the responsibility of keeping his 26-kv. lines energized in the same way as the substation operators at present are expected to keep their 4000-volt a-c. feeders or 600-volt d-c. feeders energized. When this time comes, the load dispatcher will become more of a supervising official who will concern himself more with matters of load control than that of supervising the switching of lines and transformers. One result should be a saving in time in case of outages of 26-kv. lines, in that the substation operator will be able to reclose such lines without waiting for instructions from a central load dispatcher. At times when a large number of lines is out due to lightning or other causes, delays of several minutes must necessarily occur where several substations are affected, due to the impossibility of the load dispatcher receiving reports of outages and issuing necessary orders to have the lines affected energized. While it is always somewhat dangerous to make predictions concerning future events, yet the changes that have already been made in load dispatching methods indicate that some such method of operation is likely to be the next step.

In order that the load dispatcher may have an accurate record of the system, some type of load dispatcher's board such as described in Mr. Lawson's paper, together with the necessary automatic equipment required to secure proper indications, is necessary. Since the use of this equipment enables the load dispatcher to have before him an accurate record of the system, which is correct at all times, the cost of installation and the operating cost are justified under the present conditions. However, with the growth of the system into a number of groups of substations, each fed from a suitable switching center, the transmission network would become considerably simplified and the cost of the load dispatcher's board and its leased telephone wires might be eliminated, or, certainly, considerably reduced without sacrificing any of its helpful features.

C. Lichtenberg: Centralized control became a recognized requirement of successful system operation as soon as electricity supply was furnished from two or more stations. The first step was to install a system operator, load dispatcher, or power director at some central location. He was then provided with telephone and telegraph communication with the other stations and substations. Later he was provided with system diagrams of one form or another in order to permit him readily to record changes in the system arrangement and to issue orders for system operation. Still later, means were provided to record automatically system arrangement on a system or similar diagram board. This indicated, first manually, then automatically, the position of switches and circuit breakers at all times.

One type of such an automatic supervisory indicating and control system is described by Mr. Lawson. He gives a very interesting record of its performance and some refreshing comments in connection therewith. His "experience in using the simplest as compared with the elaborate leads us to believe that the automatic indicating equipment, backed up with accessory apparatus, gives the best results as regards the safety, service, and economical handling of station load" is a typical response from an operating engineer of one of the large companies. It shows quite clearly that automatic supervisory control and indicating equipment has reached such a stage of development as to warrant its application wherever feasible to improve system operation and performance.

The broadening application of automatic supervisory control and indicating equipment will depend upon the results of development and the product of the manufacturers as well as the application and plans of the operating companies. The principles of the automatic supervisory control and indicating systems are sound. Several well tried ones are now available and they possess many desirable features. A full knowledge however of these features together with the operating requirements of an electricity supply system is necessary in order to permit successful application. Where this is done, more economical operation and better continuity of service results.

D. W. Proebstel: The centralizing of load dispatching operations is without doubt an economic thing to do where systems are made up of several important interconnected divisions. The automatic indication in the dispatcher's office of the switching operations is however a refinement, the value of which depends upon the switching complexity and the number of switching operations.

It is often the thought of those who select a location for the load dispatcher's office that it should be in the main office building "as close to the records and operating departments facilities as possible." This in many cases is a mistake. The operating department together with the load dispatchers's office should be placed at a point within the system where their functions and where automatic features of control and indication of switching operations can be attained in the simplest and most effective way.

The author stated that no indication was provided for disconnecting switches. This brings up the subject of safety to construction or repair men who might have work to do on a circuit. No circuit is safe unless the line disconnecting switches are open. Therefore, the load dispatcher, in giving clearance of a line to a workman, can only pass along the word of the station operator that a certain line has been cleared. From this view point the automatic indication of the oil circuit breakers provides the load dispatchers with only a portion of the necessary information. That portion of information is no doubt very desirable for other reasons than clearing a line for repairs. Assuming that there are no operators where supervisory control is used, it would seem that personal inspection of the switching apparatus would be necessary before permitting work on a circuit.

The experience that the Public Service Electric and Gas Co. has had with this system during the past three years has proved its worth because it has without doubt been a great factor in maintaining a high standard of service.

Automatic Power Supply for Steel Mill Electrification

BY ROBERT J. HARRY[1]

Non-Member

Synopsis.—In the production of steel, the use of electrical energy is growing rapidly. This paper outlines the present operating conditions in the Monongahela Valley System of the Carnegie Steel Company. The use of automatic switching for certain portions of this power supply has proved both economical and satisfactory.

* * * * *

WE read and hear so much these days of the extensive electrification programs of the public utilities that (electrically speaking) we are apt to overlook what is going on inside the fences which surround the modern steel mill. The utilization of the by-products incidental to the manufacture of steel, such as gas from the blast furnaces, coke dust, tar, etc., provide a source for the generation of electricity more than sufficient to meet the demands of the steel manufacturers. In most plants, all of the available sources of heat have not been utilized, owing to the fact that the demand is not so great as the supply. With the increasing demand for power, we shall see all of the available sources used and waste heat boilers will be installed wherever any hot gases are found to be passing out to the surrounding atmosphere without giving up their precious B. t. u's.

During the past few years we have seen electric drives replacing steam drives, both for main rolls and auxiliaries, so that we find many instances where a quarter of a million motor horsepower is installed in a single steel plant.

In the next few years, we shall see electricity employed in a new field which will require every available kilowatt that can be produced. The author refers to heating steel by electricity. Statistics show that this method of heating is cheaper when done under the proper conditions. It is the purpose of this paper to discuss the power system which supplies the five large U. S. Steel Corporation Steel plants in the Monongahela Valley about 10 mi. above Pittsburgh. These plants are Homestead Steel Works, Edgar Thompson Steel Works, Duquesne Steel Works, National Tube Company, and the Clairton Works.

Until about a year ago, only Homestead, Edgar Thompson, Duquesne, and National Tube Company were electrically connected. This connection consisted of a pair of 500,000-cir. mil circuits at 6.6 kv. Due to the great distances between plants, the transmission for this voltage was not very efficient, and as a result, it was impossible to transmit the required amounts of power without an abnormal voltage drop. The ability to help out an adjacent plant in case of power shortage, as well as the much better load factor that could be obtained by operating with all plants tied together, presented an economic advantage; therefore about three years ago it was decided to rebuild the system and extend it so as to include the Clairton works.

On account of this tie line operating in an industrial section where conditions are not favorable for insulation, it was some time before an operating voltage was decided upon. At first it was recommended that 22 kv. be adopted, but finally it was decided to use 44 kv. With this voltage efficient transmission can be obtained for even greater distances than at present encountered. While higher voltages were considered, it was agreed that 44 kv. was as high as could be operated with any guarantee of continuous service. The successful operation of this line leads us to the conclusion that higher voltages could be successfully employed.

Two circuits were installed, and in order to secure continuity of service under the worst conditions, it was decided to use No. 0000 copper. This enables either line to transmit at high efficiency the capacity of the largest unit on the system, which is 15,000-kw. This contingency could arise at three of the plants where 15,000-kw. units are installed. The transmission system could therefore meet this condition with one circuit out of commission.

In order to obviate the necessity of frequent periodic cleaning of line insulators, it was decided to over-insulate the line and, by means of arcing horns, reduce the flashover to ground, thereby bringing the voltage stresses on the line to a point well below the flashover value of the equipment in the substations. The line insulator units consisted of five suspension insulators whose combined rating is as follows: dry arc over without horn-gaps, 338-kv.; wet flashover, 170-kv.; dry flashover with horns, 175-kv.; wet flashover with horns, 175-kv. This compares with the manufacturers' recommendation for 44-kv. service of three units in series. It was thought that the above combination, would operate indefinitely without cleaning insulators. In some locations, however, the dirt conditions are so bad that occasional cleaning of insulators had been resorted to, and necessitated the installation of sectionalizing line switches to facilitate this procedure.

Fig. 1 shows the 44-kv. transmission system as it is at

1. Of the Alliance Machine Company, Alliance, Ohio. Formerly with the Carnegie Steel Company

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

present, and gives the distances between substations. When the two circuits are in commission, the system is always operated with the knife switches, which connect up the two 44-kv. lines on the high-voltage side of the transformer bank, in the open position. These switches are installed for emergency and single-line operation.

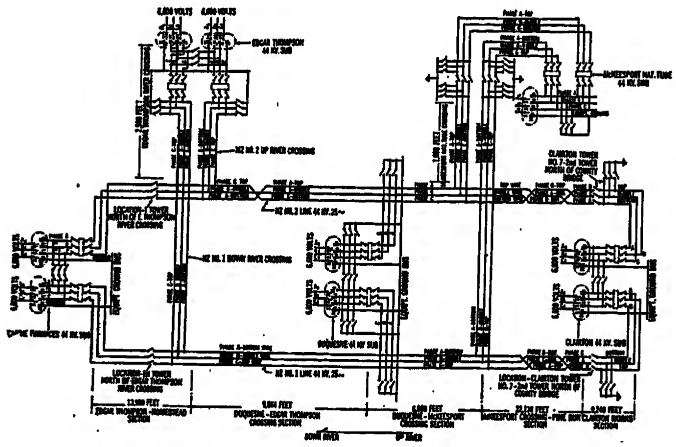

Fig. 1—44-Kv. Transmission System of the Monongahela Valley—Carnegie Steel Company

Many schemes of relaying were proposed, but none seemed to meet all of the conditions that might reasonably be expected to occur, better than did straight overcurrent and ground relays. Results of these operating experiences of more than eighteen months have been all that could be expected, and the reliability of the line has been established. In the construction of this line it was necessary to cross the Monongahela River at three points, the longest span, 2300 ft., occurring where the lines from the Edgar Thompson Works crosses the river to tie in with the line connecting Homestead and Duquesne.

The neutral on the 44-kv. side of the transformers is solidly grounded at all substations. The five substations are equipped with a total of nine 9000-kv-a., three-phase, Y-delta transformers. Two of these transformers are located at Homestead, two at Edgar Thompson, two at Duquesne, two at Clairton, and one at National Tube Company. The transformer capacity at the various plants was determined by the shortage which would be created by the failure of the largest generating unit in the plant. These transformers are equipped with tap-changing devices with conveniently arranged mechanism for changing the three phases simultaneously, and are located close to the floor. An indicating dial is also installed, as well as provision for locking in any tap position. The oil circuit breakers must be open during tap changes. It was not considered necessary to add to the cost of equipment by installing tap-changing equipment which could be operated under load. The high-tension bushings have a normal rating of 73 kv. with a dry flashover value of 240 kv. and wet flashover of 200 kv. The low-tension bushings have a normal rating of 25 kv. with a dry flashover value 100 kv. and wet flashover of 40 kv. All of the transformers are so designed that blowers can be installed to increase the rating, but only at Homestead was this extra equipment actually installed. With the blowers in operation, supplying 5000 cu. ft. of air per min. at three-ounce pressure, and the temperature of the atmosphere 40 deg. cent., a 25 per cent continuous rating above normal, or 11,250 kv-a., is guaranteed. With a larger blower, much greater capacity can be obtained. The blowers were installed on the Homestead transformers to meet the conditions arising from the shut down of one of the 15,000-kw. turbines when load conditions were at a maximum.

Current transformers are installed in the three high-tension bushings and ground bushing of the 9000-kv-a. transformers, and in the low-tension lines for differential protection. Current transformers are also installed in the bushings of the oil circuit breakers for line protection.

In order to satisfy the telephone company engineers, it was necessary to transpose the 44-kv. lines between the Duquesne and Clairton works where the power line paralleled the telephone lines.

Three of the substations are typical outdoor type, while two are indoor type. It has been found that in order to prevent the rapid deterioration of the radiators, it is necessary, where the transformers are located outside near blast furnaces, to resort to frequent painting. This may be a good application for rustless steel.

Before the five plants were connected together, it was necessary to make a study of short circuits in each plant to ascertain the proper size of circuit breakers.

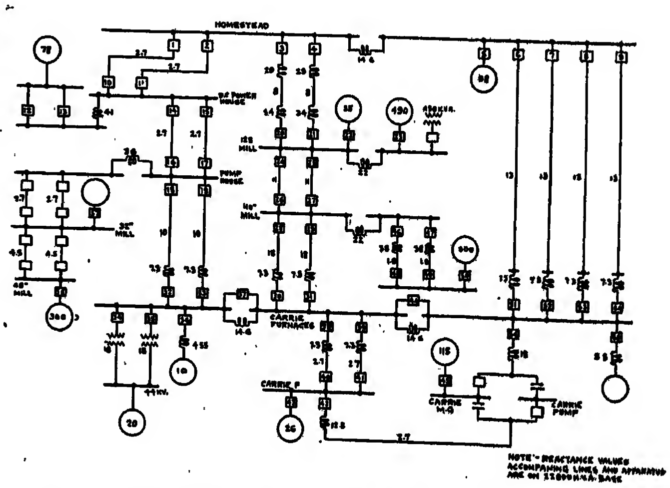

Fig. 2—Single-Line Diagram of Homestead & Carrie Furnace Works of Carnegie Steel Co. 6.6-Kv., 25-Cycle

In some of the plants, radial feeders with proper current limiting reactors are installed, while at other plants loop circuits are employed. In order to reduce the short-circuit values to a point where the circuit breakers could meet the thermal and interrupting capacities, it was necessary at some of the plants to insert reactors in the station bus.

At the Homestead Works, a loop system is in operation. When completed, it will be as shown on Fig. 2. At the Carrie Furnaces, only two turbo generators are installed at present, although provision has been made for a third unit. The oil circuit breakers have sufficient capacity to meet the proposed increase in generating capacity. Reactors having a continuous capacity of 2000 amperes are installed in both front and back busses, and oil circuit breakers installed to short-circuit the reactors when operating conditions require. The size of this equipment permits the transfer of the entire capacity of a 15,000-kw. generator to any part of the bus for distribution either through switch or reactor. Under normal operating conditions, the feeder circuits are so arranged that very little power is transmitted through the bus reactor.

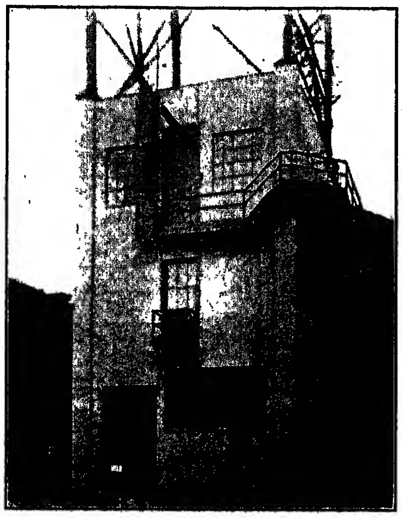

Fig. 3—View of Tower Substation on the Homestead Loop System

Since continuity of service is of prime importance in the operation of steel mills, adequate protective relay equipment was installed to provide selectivity in case of fault, and at the same time not involve too much complication. Four parallel feeder circuits were installed between the Carrie Furnaces generating station and the New Structural Mills. These circuits are equipped with current balance, back-up overload, and ground relays. Owing to the large amount of synchronous equipment fed from each substation, selective relay action is obtained. The induction type overload relays have a high setting and function in case of bus faults.

Reactors were installed at strategic points in the loop system so that only that portion of the system in which the fault occurs is affected, sufficient voltage being maintained in the other parts of the system to prevent losing the synchronous load. While the above reason would be sufficient to warrant the installation of reactors, their economic value is of considerable importance. The reactors installed in the loop stations between the bus and feeder circuits permit the use of small oil circuit breakers with the same margin of safety that obtains with the use of larger breakers on the other side of the reactor. This can be illustrated by the fact that the loop bus at the d-c. power house is equipped with breakers having an OCO + OCO rating of 36,000 amperes at 6600 volts, while the feeder breakers on the other side of the reactor have a big safety factor with an OCO + OCO rating of 8500 amperes at 6600 volts. When it is considered that there are 22 small feeder breakers installed in this location, the economy made possible by the use of reactors is very apparent. The reactors also prevent the extremely heavy currents with their resultant stresses from getting to the small feeder circuits and equipment connected to them.

The loop circuits are of overhead construction, located on towers, and involving two river crossings. The towers at the loop stations are of special design, and in addition to supporting the lines, have a three-story building with a 30-ft. by 25-ft. floor area located in the bases. Figs. 3, 4, 5, and 6 show views of one of these combination towers and substations. The lightning arresters are outside valve type and are accessible from the roof. The oil circuit breakers (Fig. 6), are located on the third floor, the reactors (Fig. 5) on the second floor, and the ground floor provides sufficient space to house power and lightning transformers.

The oil circuit breakers are of the metal-clad lift type which permits of unit assembly at the manufacturers' plant, and provides for easy additions in the field. All substations can easily take care of the distribution of 10,000 kw. which provides for future installation. In the substations, 32-volt storage batteries are installed for tripping the oil circuit breakers and to provide a source of light in case of power failure. Since nothing would be gained by closing the breakers before power was restored, a motor-generator set with automatic switchboard to provide 250 volts direct current for

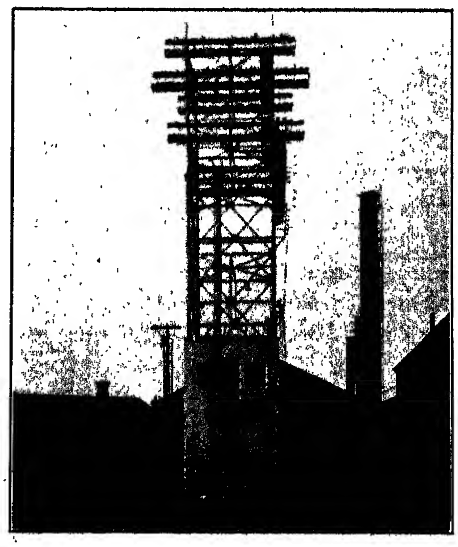

Fig. 4—Another View of Tower Substation on the Homestead Loop System

closing the breakers was installed. This motor-generator set is small, and 250 volts emergency is obtained in a few seconds after the 6600-volt lines are energized.

At the New Structural Mills, an automatic substation is installed. It consists of three 1500-kw. motor-generator sets operating at 500 rev. per min., the motor being of the standard synchronous type arranged for compensator starting and the generator being compensated shunt-wound.

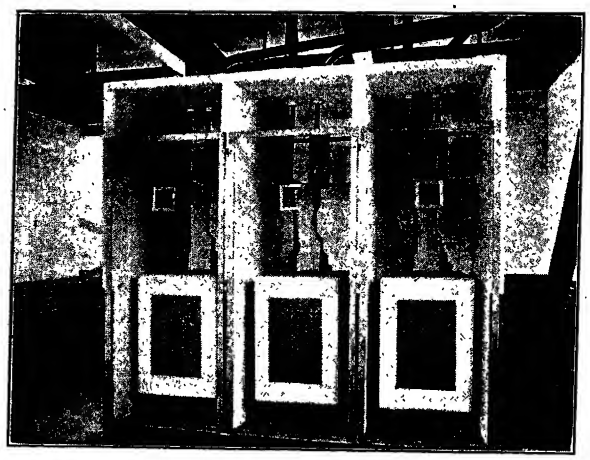

Fig. 5—Views of Tower Substations on the Homestead Loop System

The reason for making this substation automatic was to reduce operating costs. These sets, located in the large mill motor room building, are shown in Fig. 7.

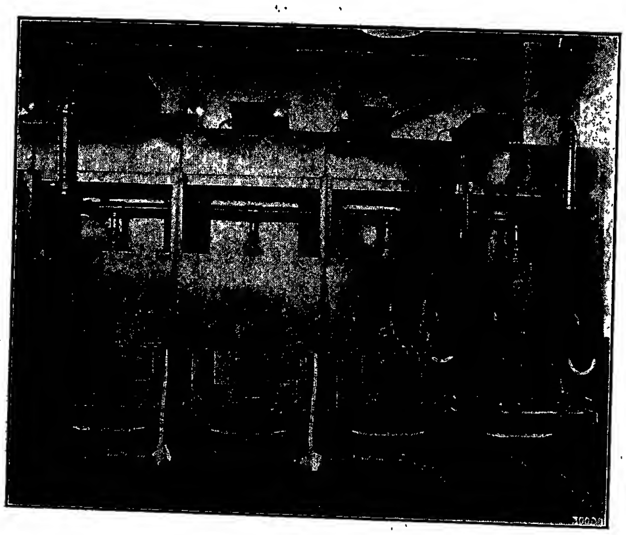

Fig. 6—Views of Tower Substations on the Homestead Loop System

The figure shows but two sets, the third set having been added recently. Provision was made in the switchboard shown in Fig. 8 and foundations provided for this contingency. This room, a general view of which is shown in Fig. 10, also contains seven main roll drive motors, with their motor-generator sets and auxiliaries. The duties of the two men employed in this room require them to spend considerable time in the basement where the air conditioning equipment, fans, truck type oil circuit breakers, etc., are located; and they are therefore unable to spend much time at the motor-generator sets. Because of this, it was considered safer to depend on the automatic features, which are continually on the alert and ready at all times to do their assigned duty, rather than upon an operator who may or may not be on the scene when trouble occurs to the equipment.

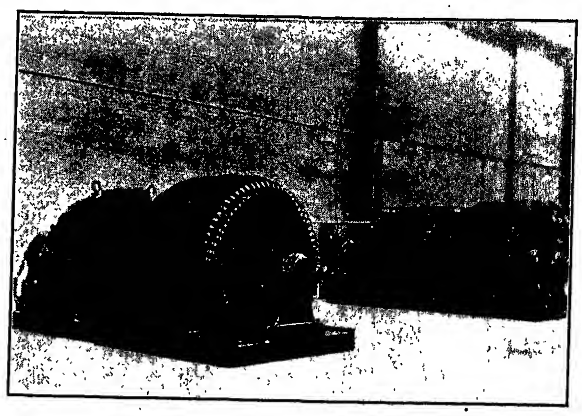

Fig. 7—Two 1500-Kw. Motor-Generator Sets in the Homestead Substation

There were many automatic features which could have been installed, but which were omitted on account of the added cost and complications not warranting their installation, and because two men are always in the building.

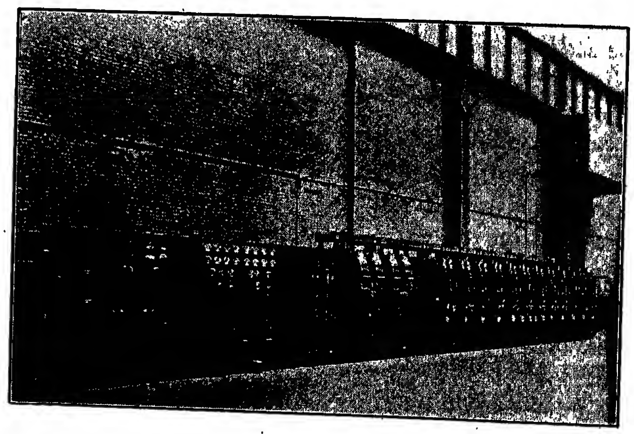

Fig. 8—Automatic Switchboard for the Control of the Motor-Generator Sets

The third set is now in operation, the control boards replacing the blank panels in the picture

The substation is equipped with the following features:

1. Individual, truck-mounted, line-starting and running oil circuit breakers, and starting auto-transformers are provided for each motor-generator set, and one common cell housing for the necessary potential transformers is provided for all sets.

2. The normal d-c. control is taken from a constant source.

3. Push-buttons are used to start all units.

4. After the unit has attained synchronous speed, a three-element regulator balances the generator voltage against line voltage and then connects the generator to the bus. The regulator then operates to maintain constant voltage on the d-c. bus. A load-limiting element regulates the load that can be taken from the generator.

5. The d-c. feeders open only on short circuit and reclose automatically after a suitable time element and the removal of fault.

6. Equipment is installed to protect against:

(a) Single- and reversed-phase starting; (b) a-c. undervoltage; (c) a-c. overload; (d) field failure; (e) wrong polarity; (f) reverse power; (g) overheated motor winding; (h) hot bearings; (i) d-c. and a-c. ground protection; (j) overspeed; (k) d-c. overload; (l) overheated starting compensator; (m) overheated generator windings; (n) undervoltage connection to d-c. bus.

The results obtained from more than four years of operation have been entirely satisfactory and we do not

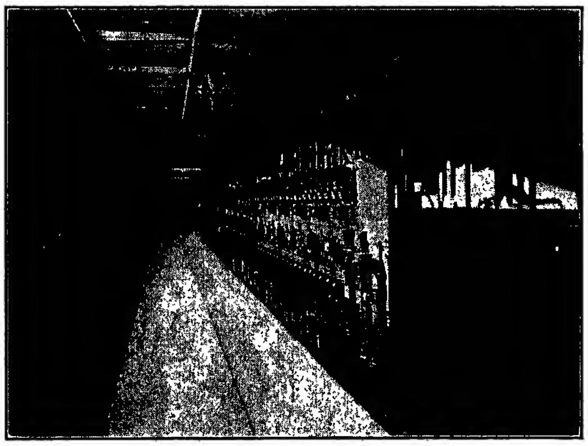

Fig. 9—Underground Installation of Mill Table Controllers

in any way regret the decision in favor of the automatic equipment. To date, no automatic features have been discontinued and no failures or emergencies have made necessary the installation of additional protective or automatic equipment. While some minor troubles were experienced when the station was first put into service, after all adjustments had been made the reliability of the equipment has met our most optimistic expectations. Some faulty operations of the feeder breakers have occurred where the acceleration currents drawn by large motors approximate short-circuit conditions, and the impulse coils on the feeder circuits find it very difficult to differentiate between these conditions when they have practically the same steep wave front.

One item which must be kept in mind when making installations of this size, is the bracing of the d-c. bus bars. Bus short circuits which occur on feeder circuits close to the substation produce tremendous stresses which will destroy the bus structure unless very rigidly braced to withstand the stresses.

In cases where one station is tied to one or more other substations by suitable tie lines, these tie lines should be equipped with high-speed breakers. These breakers should have a very definite tripping current which will permit sending over these lines all the current the station can in safety put out and provide for normal interchange of power. In case of substation outage, currents of much greater magnitude would be involved,

Fig. 10—General View of Automatic Substation at Homestead

Two of the three present sets with automatic switchboard may be seen in left foreground

and the high-speed breakers would separate the good substations from the faulty one before the standard circuit breakers would have time to function. This equipment would prevent many of the d-c. total outages.

It has been found that, where electric equipment is isolated from the mill equipment and installed in buildings where it can be kept clean, little trouble can be expected. This is true not only of substation and mill motor equipment, but holds equally true for auxiliary equipment. Where possible, mill auxiliary controllers are grouped and installed in houses or in tunnels directly under the equipment. Fig. 9 shows a typical installation of a group of controllers for mill tables. This type of installation provides for easy inspection and maintenance.

The reliability of the equipment entering into the construction of the modern automatic substation, and the greater protection obtained from the use of modern relays which possess almost human intelligence and indefatigable alertness, will result in the installation of a greater number of these equipments in the steel plants.

Discussion

C. Lichtenberg: The title of Mr. Harry's paper is a most fitting one. It is indicative of the present day trend toward automatizing. It describes the application of automatic switchgear to an important steel mill where continuity of electricity power supply is measured directly in terms of production cost.

One item is of particular interest. It is the mention of some faulty operations of the feeder equipment which occurred when the acceleration current drawn by large motors approximated short-circuit conditions. This may have been due to inherent limitations in the design or in the application.

Discrimination between normal and abnormal current rushes is exceedingly difficult when the impulse ratios approach each other. However, the development of the art is producing solutions which meet the requirements indicated by Mr. Harry.

The testimony, "Results obtained from more than four years of operation have been entirely satisfactory, and we do not in any way regret the decision in favor of the automatic equipment," is very encouraging. Operating engineers the world over are turning to automatic switchgear to solve the service continuity problem. They are finding that electrical devices which operate in response to circuit conditions are inherently very much more prompt, and in general more reliable than humans. Of course, this is not just accidental. It is the result of close cooperation and collaboration of the manufacturers and the operators during the past 15 years. In this period they have spent much time, money and energy, as well as inventive talent toward making automatic switchgear simpler and more reliable, at the same time keeping the cost within limits, so as to make "automatics" more economical than the conventional equipment.

R. J. Harry: Mr. Lichtenberg states that relays are now being developed having greater discriminating characteristics than those formerly used. This will undoubtedly result in fewer faulty operations and also bring this type of equipment more into favor. Automatic equipment has already reached such perfection that it is much more reliable than human attendants and few substations are being installed at present that do not contain some automatic features.

As automatic switch gears become more simplified and consequently more reliable, it will undoubtedly, to an increasing extent, crowd out the non-automatic type.

1000 Kw. Automatic Mercury Arc Rectifier Substation

of the Union Railway Company of New York

BY W. E. GUTZWILLER[1] and O. NAEF[1]
Non-member Associate, A. I. E. E.

Synopsis.—A 1000-kw., 625-volt automatic mercury arc rectifier substation, installed by the Union Railway Co., of New York, in May, 1929, is described in general in this paper together with the account of the automatic and remote control features of the substations. The principle reasons for the adoption of the mercury arc rectifier are mentioned and operating and performance data for the first ten months' operation are presented.

* * * * *

INTRODUCTION

IN May, 1929, the Union Railway Company of New York put their first automatic rectifier substation in operation. This substation contains a 1000-kw., 625-volt rectifier set, which is supplied by 13,200-volt, three-phase, 60-cycle current. Its control is a combination of automatic load responsive and remote control. Provision is made for operation of the set on either 25- or 60-cycle.

The installation is noteworthy, inasmuch as full benefit has been derived from the many advantages the mercury arc rectifier has over rotating converters. Such advantages are adaptability to automatic and remote control, operation on two frequencies, small weight and space, and absence of special foundations,—all resulting in low installation costs.

A description of this installation is given herein, with particular reference to automatic control.

DECIDING FACTORS IN THE CHOICE OF AUTOMATIC RECTIFIER

The 1000-kw. automatic rectifier substation in question supplies power to the street-car system of the Westchester Square Section, Bronx, N. Y. Previous to the installation of this rectifier, the d-c. power for this section was supplied from the Union Railway Company's substation at West Farms, located approximately three miles from Westchester Square. This substation is manually operated and contains 5000 kw. in 25-cycle rotary converters.

Due to a steadily increasing load in the Westchester Square Section, these converters, which are over 15 years old, could not for much longer handle the increased demand from this section, so that the railway company decided to install additional converting capacity. It was estimated that at least 1000 kw. of additional machine capacity was needed to take care of the present and future power requirements in this section. In order to reduce feeder losses to a minimum, it was decided to place the new converting equipment in the Bronx Gas & Electric Co.'s transformer substation at St. Peters and Westchester Avenues. This substation is located right in the center of the Westchester Square Section, where additional power was required. The new unit was to be equipped with full automatic control and provided for remote operation and indication from the railway company's station at West Farms.

For this new substation, both rotary converters and mercury arc rectifier were considered, but after a careful investigation the choice fell in favor of the rectifier. The principal reasons for the Union Railway Company's choice of a mercury arc rectifier were as follows:

A 1000-kw. rectifier set could easily be installed in an available corner space in the above mentioned substation, while considerably less rotary converter capacity could have been accommodated in the same space.

While all the converting equipment of the Union Railway is of the 25-cycle type, 60-cycle converting apparatus had to be provided for this new substation, as only 60-cycle power was then available. Inasmuch as it was questionable, however, whether 25- or 60-cycle equipment would be used to greater advantage at some future time, it was highly desirable to provide the new converting equipment for operation on 25- and 60-cycle. Here again the mercury arc rectifier proved to be the ideal apparatus, since it is not affected by the frequency of the supply system. The rectifier transformer, of course, had to be designed for operation on both frequencies.

Since the space in the substation had to be rented from the power company, and also in view of the expiration of the power contract, it was desirable to install the new equipment at a minimum cost. In this respect the mercury arc rectifier also met all requirements, as it needs no special foundation; it could be set on the existing substation floor without any reinforcement. The rectifier required no ventilating ducts nor openings in the walls or roof for ventilation, (such as is the case with a rotary converter), as practically all its losses are carried away by water.

Due to the stationary character of a rectifier, automatic and remote control is very simple and the costs of the control apparatus are low. Due to the simplicity of the control, only very few conduits for control wiring

1. Both of American Brown Boveri Co., Inc.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

had to be provided. The conduits, as well as all the low-voltage power cables, could be installed over head, thus obviating any changes whatsoever in the building structure. Remote control from West Farms Substation, approximately three miles away, could easily be provided without much extra expense. Only eight control wires were required for remote control and indication. From Fig. 1 showing the substation layout, it can readily be seen that the rectifier apparatus fully utilizes the available space, yet sufficient clearance exists between the apparatus for inspection.

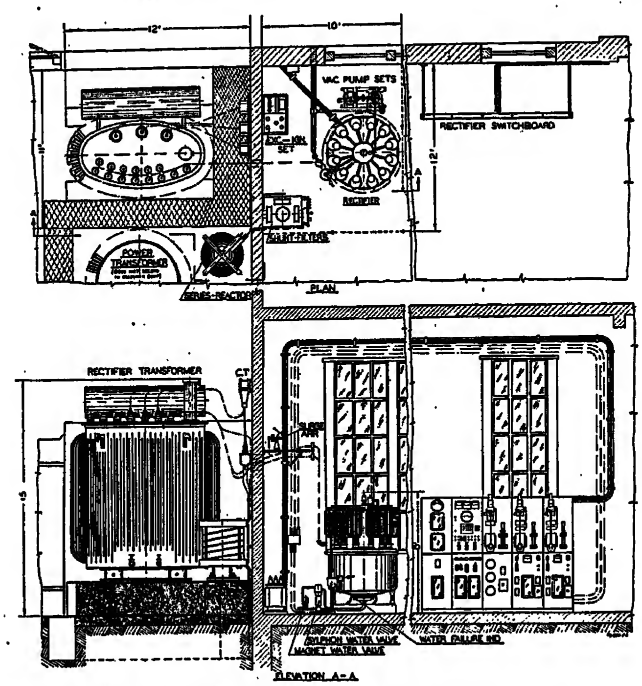

Fig. 1—1000-Kw. Automatic Rectifier

Description of the Equipment

The 1000-kw. automatic rectifier plant consists of one 1000-kw. nominally rated rectifier unit. Energy is taken either from the 13,200 volts, three-phase, 60-cycle station main bus or from the station auxiliary bus and converted to 625 volts, d-c. The rectifier and its transformer are capable of carrying the following loads, based on the nominal rating of 1000 kw. at 625 volts, at 25 or 60 cycles:

Load in percentage	Ampere	Duration
100	1600	Continuously
150	2400	2 hours
200	3200	1 minute

All apparatus pertaining to the rectifier plant, including automatic and remote control apparatus, cables, bushings and busbar material were furnished and installed by the American Brown Boveri Co., Inc., with the exception of the two 13,200-volt oil circuit breakers. These breakers were already available in the substation.

Since mercury arc rectifiers and their standard auxiliary apparatus of similar types have been described before, this apparatus shall be mentioned in the following only in a general way.

The rectifier cylinder is of the 12-anode type and is cooled by fresh water. The anodes are water cooled. Fig. 2 shows the rectifier cylinder. As the rectifier tank when in operation is under d-c. potential, it has been surrounded by a protective screen.

The rectifier receives energy from an oil insulated, self-cooled, tubular type outdoor transformer. The transformer is provided on the primary side with one plus and one minus 3½ per cent full-capacity tap and ratio adjuster for no-load operation. The secondary is connected in double six-phase star. Due to space limitation, the interphase transformer which usually is built into a separate tank, has, in this case, been built directly into the rectifier transformer. The transformer is designed for operation on either 25- or 60-cycle, 13,200-volt, three-phase current. At 60-cycles, the transformer has an impedance of 4.5 per cent. When operated on 25-cycle, it is necessary to connect an external reactance of 3 per cent in series, in order to protect the transformer. Fig. 3 shows the rectifier transformer from the low-voltage side, completely assembled. On account of the 25-cycle rating and the built-in interphase transformer the over-all dimensions of this transformer are somewhat abnormal.

The pumping equipment for exhausting the air from the rectifier cylinder consists of a water-cooled mercury vapor pump, connected in series with a motor-driven rotary oil pump, all mounted on a common frame.

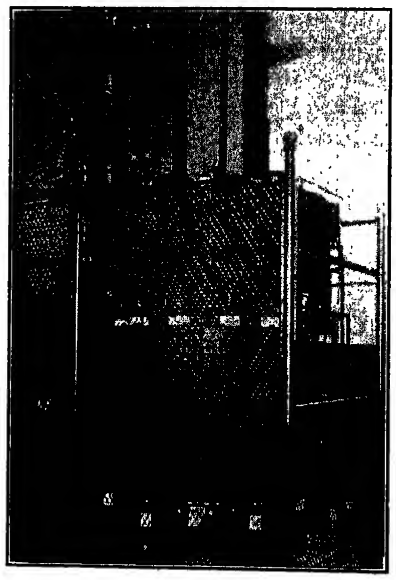

Fig. 2—1000-Kw. 625-Volt Mercury Arc Rectifier

The ignition and excitation apparatus is mounted on a common angle iron frame and operated from a single-phase and low-voltage auxiliary supply.

The vacuum measuring device, as well as all the automatic control apparatus, are operated from the same a-c. supply. The power for the rectifier auxiliaries is taken from a 220-volt, 60-cycle, two-phase, three-wire circuit, which is separately metered.

On the d-c. end, the rectifier is connected to the bus through a single-pole, 3000-ampere solenoid-operated breaker, with overload and reverse current trip.

Two 2000 ampere automatic reclosing feeder breakers connect the rectifier bus with the load.

The rectifier switchboard consists of five 24-in by 90-in. slate panels. Fig. 4 shows the rectifier switchboard. Starting from the left hand side, the first

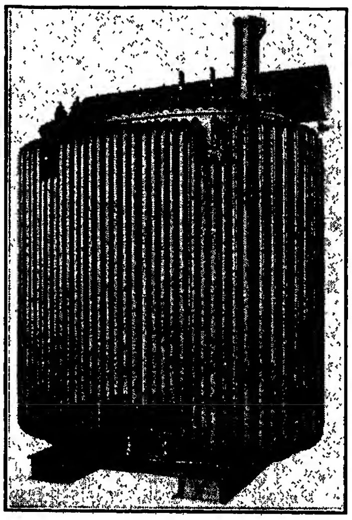

FIG. 3—1000-KW. 13,200-VOLT, THREE-PHASE, 2 x 6 PHASE 25/60-CYCLE RECTIFIER TRANSFORMER

panel contains the apparatus for automatic starting and stopping of the rectifier set. The second panel contains the rectifier indicating instruments, the vacuum measuring device, drop annunciators, receptacles, and plugs

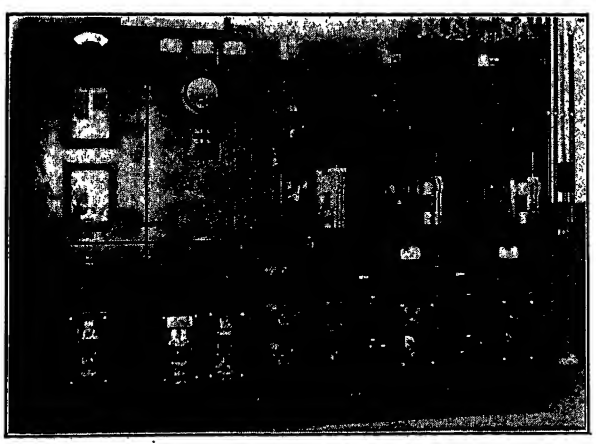

FIG. 4—RECTIFIER SWITCHBOARD OF 1000-KW. AUTOMATIC SUBSTATION

for various methods of control, control switches for rectifier auxiliaries and circuit breakers; also, the automatic control apparatus for the vacuum pump set. The third panel contains the rectifier d-c. breaker and knife switch, breaker-control relay, and induction type overload relays. The fifth and sixth panels each contain a feeder breaker with knife switch, ammeter, and automatic feeder reclosing apparatus.

For overvoltage protection between anodes, each secondary phase of the rectifier transformer is connected through a damping resistance to a horn-gap arrester. The other side of each arrester is connected to the common neutral of the transformer.

The rectifier set is provided with a filter equipment designed for the purpose of suppressing the ripple in the d-c. output of the rectifier to a point where it will not cause objectionable interference with telephone circuits. The equipment consists of a series reactor connected in the negative lead of the rectifier and three shunt filters, tuned for 360, 720, and 1080 cycles, which are the most disturbing frequencies for communication circuits. The series reactor offers a high impedance to the alternating currents of above mentioned frequencies and limits them to such values as can be

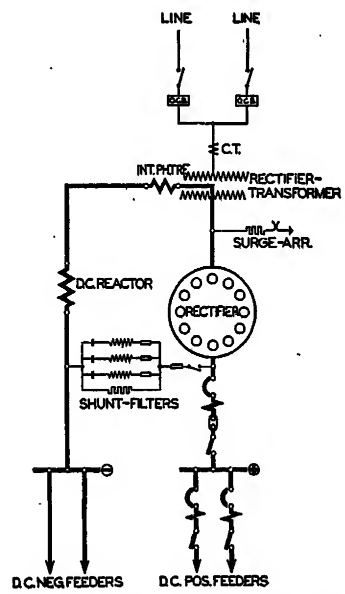

FIG. 5—1000-KW. AUTOMATIC RECTIFIER

economically taken care of in the shunt filter. Each shunt filter is a resonant branch for one of the above mentioned frequencies and therefore provides a short-circuit path for the particular frequency for which it is tuned. The series reactor is located outdoors while the shunt filter with necessary fuses and knife switches mounted on a pipe frame, are located indoors within the enclosing screen of the rectifier.

Fig. 5 shows the single-line diagram of the rectifier plant.

DESCRIPTION OF AUTOMATIC AND REMOTE CONTROL

Since the automatic control of this rectifier plant is typical for a railway substation of this type, a more detailed description of the control is given hereafter: The following paragraphs will describe not only the method of control actually in use in this substation, but also the method which would be employed should one or more units be added to the present installation. In addition, certain features which are not being utilized

now, but are available and may be of importance in the future are described.

The following description of the automatic controls will be divided into five groups; namely, control of auxiliaries, control of the rectifier, plant or master controls, a-c. feeder control and d-c. feeder control. The remote control, being a particular feature of this substation, is dealt with in a separate paragraph.

I. Control of Auxiliaries.

The auxiliaries of a mercury arc rectifier consist of the excitation-ignition set, the cooling equipment, and the vacuum pump set. The excitation-ignition set is energized by the closing of the a-c. breaker and maintains the excitation arc so long as the a-c. breaker is closed. In the same way, the magnet water valve controlling the rectifier cooling water is opened by the closing of the a-c. breaker. Where recooling is used instead of fresh water, the circulating pump and fan motors are similarly started with some modification in the control.

Vacuum Pump Control. Unlike the excitation-ignition set and cooling apparatus, the vacuum pump operates independently of the rest of the plant, but so as to maintain the vacuum in the rectifier. The contact-making vacuum meter is the nucleus of the vacuum pump control. Associated with it is the vacuum pump control relay, which also takes care of several protective functions necessitated by the nature of the vacuum pump set.

The gases are pumped from the rectifier in two stages by a mercury vapor pump and a rotary vacuum pump. The mercury vapor pump creates a high degree of vacuum, but only against a comparatively low back pressure. The rotary pump carries off the gases drawn from the rectifier by the high vacuum pump. A reservoir and an automatic valve are placed between the two stages so that continuous operation of the rotary pump is unnecessary. On the other hand, the high vacuum pump must operate continuously.

Since the vacuum attained by the rotary pump is insufficient for safe rectifier operation, this pump must never be permitted to operate alone. Therefore, should the high vacuum pump fail for any reason, such as failure of auxiliary power or water failure,—the mercury vapor pump requires a continuous flow of cooling water while in operation—both pumps are shut down. When the trouble is cleared, normal operation is automatically resumed after a preliminary heating of the high vacuum pump lasting approximately a quarter of an hour. The reason for this time delay is that the mercury vapor pump cannot produce a sufficient vacuum before it reaches the proper temperature.

II. Control of the Rectifier.

The control of the rectifier means the actual starting and stopping of the rectifier. In starting, the oil circuit breaker is closed first, energizing simultaneously the ignition-excitation and the rectifier cooling water valve. The d-c. breaker closes last, whereupon the rectifier immediately takes its share of load. The starting requires one to two seconds. In stopping, the oil circuit breaker opens first, tripping the d-c. breaker and stopping the excitation and the water at the same time.

A-C. Closing and Reclosing. The oil circuit breaker is controlled by the a-c. closing and reclosing relay, which makes three attempts to close the breaker, either on initial starting or after opening on overload. The third unsuccessful attempt to close automatically locks out the oil circuit breaker.

Protection. The rectifier is protected against sudden or continuous overloads, reverse current due to backfire, operation with poor vacuum, excessive temperature, and cooling water failure.

Induction overload relays provide short-circuit protection, while a thermal overload relay takes the rectifier out on continuous overload for the length of time required to restore normal temperature.

When a backfire occurs while the rectifier is paralleled with other machines, the reverse current trips the d-c. breaker, which in turns opens the oil circuit breaker through a special high-speed interlock. This interlock is extremely simple and effective. A current transformer trip coil on the oil circuit breaker is connected in the circuit of a current transformer in the primary of the rectifier transformer. When the d-c. breaker is closed, this trip coil is short-circuited by a contact on the d-c. breaker. When the d-c. breaker is tripped by backfire this short-circuit is removed and the current transformer trip coil will trip the oil circuit breaker. The interlock and tripping do not depend on auxiliary or control bus voltage and therefore attain the highest dependability.

The rectifier is locked out when the vacuum pump is unable to maintain proper vacuum, which indicates a leak in the rectifier or trouble in the pump. Lockout also occurs in case of excessive temperature in the rectifier cylinder, if beyond the control of the overload protective devices. Lockout can only be reset manually. Water failure merely trips the d-c. breaker after an interval of about one minute and holds it open until the flow is restored.

III. Plant Control.

The plant control includes all devices and circuits which are used to stop and start the plant. The plant control in this substation, consists of load responsive and remote control. In case of load responsive control, either low voltage on the bus or the occurrence of low current will start the time-delay, start-and-stop relay. If these conditions persist over a period adjustable up to 60 sec. in case of low voltage, and 15 min. in case of low current, this relay will give the start or stop signal to the a-c. closing and reclosing relay. Instead of, or in addition to the load responsive control, a time switch may be provided.

Where there are two or more units in a station, one unit is generally controlled by the master elements

(*i. e.*, load responsive control, remote control, clock or manual control) while the others are switched in or out according to the load on the first unit. These units are then designated as leading and lagging units respectively. Should the leading unit be locked out, the signals from the master elements are automatically transferred to a lagging or reserve unit. This method of control is known as the "transfer-lockout" control. Any one, or a combination of the master controls may therefore be used, and can be obtained by the manipulation of a selector switch. Any unit may be made a leading, lagging, or reserve unit by means of the selector switch.

Remote Control. In this installation, the plant can be controlled by the supervisor at West Farms Substation. He has continuous indication of the positions of all breakers and can, at will, assume control or relinquish it to the master controls in the station, without the necessity of having someone change the position of the selector switch.

IV. A-C. Feeders.

The station is supplied by two a-c. feeders which may furnish the power singly or jointly. For simplicity of control, and to avoid the use of an additional breaker for the rectifier, an electrically operated change-over switch is so connected to the auxiliary contacts of the two feeder breakers that when either breaker or both breakers are closed, it is in a position corresponding to "breaker closed" and only when both breakers are open is it in a position corresponding to "breaker open." For control purposes therefore, this change-over switch may be regarded as a "phantom" rectifier a-c. breaker whose position indicates whether the power is on or off the rectifier. The control relays for the rectifier mentioned in Paragraph II operate directly on the a-c. feeder breakers. Where mention is made of the rectifier a-c. breaker or oil circuit breaker in connection with the automatic controls in this substation, the phantom breaker is understood.

Due to the fact that the substation is very close to a ring bus the automatic reclosure of the a-c. feeder breakers has not, so far, been permitted, on account of the voltage dips which might occur when the breakers close on short circuits. Manual control switches in series with the closing contacts of the reclosing relay are therefore provided on the company's control board located in the same substation. The breakers, then, cannot be closed, unless the manual control switches are operated and the reclosing relay is in its closing position. Tripping can be accomplished either by the rectifier control and protective relays or by the power company, independent of each other.

During the past ten months of the operation of the rectifier plant, no disturbances which could have resulted in an automatic reclosure on short-circuit have occurred. There is no question but that the Union Railway Company will soon be permitted to derive the full benefit of its automatic equipment.

If desirable the a-c. feeders can be arranged for "preferred feeder" control. The change-over from the preferred to the emergency feeder is done automatically in this case and when the trouble is cleared the supply of power is transferred back to the preferred feeder. Either feeder can be made preferred by means of a selector switch. This type of preferred feeder control is also applied when power is supplied at 60 cycles over one feeder and at 25 cycles over the other feeder. In this case, a series reactor is installed in circuit with the 25-cycle feeder for transformer protection and for maintaining the same regulation of the rectifier d-c. voltage as at 60 cycles.

V. Automatic Reclosing D-C. Feeders.

There are two automatic reclosing d-c. feeders in this substation. The feeder breakers are normally closed. When tripped by overload, the d-c. feeder reclosing relays will attempt to reclose them a predetermined number of times at predetermined time intervals. After the scheduled number of attempts have failed to close a breaker, it is locked out.

A city ordinance requires that the supervisor have the ability to disconnect any trolley feeder when called on to do so. For this reason the feeders are also equipped with remote control, so that they can be locked out and reset by the supervisor.

Remote Control. Since the remote control plays such a prominent part in this substation, it is thought advisable to devote a few words to the system employed.

The remote control station is at West Farms Substation, about three miles away. The connections between the two stations are made over a telephone cable. The scheme requires a 110-volt battery at each end of the cable, a polarized relay in the substation for each breaker to be controlled, and one at the remote station for each breaker for which indication is desired. One wire is required for each relay; that is, one for the indication and one for the control of each breaker. There is one common wire joining the midpoints of the two batteries. Where only one battery is available, two extra wires must be used.

The breakers controlled are the a-c. feeder breakers and the two d-c. feeder breakers. Indication is provided for the phantom a-c. rectifier breaker, the d-c. rectifier breaker and the two d-c. feeder breakers. Eight wires are therefore needed for the complete remote control of the station. The remote control plays the same part in the control of the plant as the other master elements, except that its signals predominate all but the protective relay signals. It therefore controls the position of the a-c. closing and reclosing relay, which, in turn, controls the breaker of that a-c. feeder which has been selected for reclosing operation.

In connection with the remote control, mention might be made of an inexpensive scheme of remote metering, devised and installed by the railway company. The scheme utilizes the d-c. voltage drop across the series reactor of the telephone interference equipment, to give

an indication of the rectifier load at West Farms. A millivolt meter at West Farms, calibrated with the line drop, indicates the load on the rectifier in amperes. The voltage drop across the reactor consists of a d-c. component and several a-c. components. In order to reduce the a-c. component in the current through the millivolt meter, a small reactor was installed in the leads. The accuracy of this remote metering equipment has been found entirely sufficient for practical purposes.

Operation and Performance Data. The rectifier unit has been in successful operation since May, 1929. The set is in service daily from 6:00 a. m. to 10:00 p. m. Every Sunday morning, at times of low load, the set is taken out of service for cleaning and a short inspection.

Up to March 1, 1930, a total a-c. input of 2,334,800 kw-hr. had been metered on the rectifier. No d-c. watthour meters are installed in this plant. It follows from this input figure that the average monthly power consumption was 233,000 kw-hr. which corresponds to a daily load factor of 45 to 50 per cent.

Over the same period, the metering of the rectifier auxiliary power indicates a consumption of 17,300 kw-hr., corresponding to 0.75 per cent of the total rectifier input.

No official efficiency measurements have been carried out on this set, but measurements taken with available switchboard instruments indicate that the guaranteed efficiences are met.

Measurements of the cooling water consumption of rectifier and vacuum pump are available only up to October 10, 1929, and indicate that up to that date 77,500 cu. ft. of water had been consumed, corresponding to 0.068 cu. ft. per kw-hr. rectifier input. Assuming the load factor to be the same over a period of 12 months, as computed from the first 10 months of operation, the yearly cooling water consumption, for this rectifier set, will amount to approximately $190. This figure is based on a water cost of $1.00 per thousand cu. ft.

Through trolley wire and feeders, the rectifier set is operating in parallel with rotary converters of the neighboring substation. The rectifier is taking the proper share of the system load and no difficulty whatsoever has been experienced in parallel operation.

As already mentioned, a filter equipment has been installed for suppressing the a-c. ripple in the rectifier output. This filter equipment has been working satisfactorily and no complaint of telephone interference in communication circuits has been received.

CONCLUSION

In the foregoing article a 1000-kw. automatic mercury arc rectifier installation has been described, with particular reference to its automatic control. The installation is a practical example to show that a rectifier can, without too much complication, be provided for automatic and remote control, that it can be installed in a very limited space without any changes to existing building and floor. Furthermore, the rectifier can be provided for operation on 25 and 60 cycles, where power at both frequencies is available, or may be considered in the future.

Miniature Switchboards

A Modernization in the Design of Operating Switchboards for Electric Power Stations and Substations

BY PHILIP SPORN[1]

Member, A. I. E. E.

Synopsis.—This paper points out the general progress made in the design of electric power systems and contrasts with it the lack of progress in the field of control switchboards. It is shown that due to this lack of progress a situation confronts many systems today where switchboards are so large that excessive amounts of space are necessary for their housing and further expenditures are later necessary in order to integrate these large switchboards so as to bring them within proper supervisory control of a limited number of operators. A development in miniature switchboards is described embracing and containing all the fundamental requirements of a control switchboard and yet with no greater space than 4 in. of panel width for complete control and supervision of one feeder. A description of the instrument, control switches, and auxiliary relays is given as well as the method in which all these elements have been assembled. Drawings and photographs of actual installations showing the possibility of developing a switchboard along the lines described, that will handle 60 feeders and yet bring it within the range and operating control of a single operator, are given. The advantages of the new development are, as brought out: Compactness, ease of operation, closer supervision, ease of erection, good appearance, and modernity.

I. Introduction

The progress made in the design of central stations, substations, and switching stations in the past two decades is too well known to those associated with the electric light and power industry to require any extended description. There has been tremendous improvement in the design of boilers, turbines, transformers and similar and related equipment, as well as development and extension of the maximum economic sizes, resulting in each case in larger, more compact units, with decrease of the space required per kw. All this, as may perhaps not be apparent, is part of a general movement,—a part of a very pressing economic drive to obtain a kilowatt of capacity for less investment. That this is one of the most vital problems facing the electric power industry there can be no doubt; but, unfortunately, by the time it reaches the switchboard the importance of this vital movement is very often lost sight of.

It is only necessary to examine switchboards of today and compare them with those of 10 or 20 years ago to be impressed with the truth of this situation. Today we find switchboards perhaps with better wiring or with other refinements as compared with those which were built a decade ago, although substantially of the same type. Generally employed there is a panel—anywhere from 12 to 30 in. wide,—to control an individual circuit or portion of the apparatus. It is true that this particular circuit may be handling more power than was handled by a corresponding circuit 10 years ago, but this is exactly the sore point. The advance has been in the circuit itself; the switchboard design has not made a corresponding advance.

It is true that there have been some changes, but in the main there has been no fundamental progress. Thus we have seen the development of the back-to-back board, which has cut down the over-all length necessary for the control of a given number of circuits. On the other hand, in many instances the development of the idea of placing a bench board in front of the back-to-back board has resulted in requirements of greater cubage.

As a typical example of what this has led to, we can cite a case of one of the most modern steam plants placed in service within the last month or so, with two 58,000-kw. units and one 15,000-kw. unit, where a control room approximately 97 ft. by 30 ft. was provided. After allowing for an ultimate layout of approximately 600,000 kw., the control room is found to be very definitely and uncomfortably crowded.

The general result due to this lack of progress in switchboard design may be said to have been, that the boards for the average station or substation have grown in size and reached a point where an ordinary operator, or even a group of operators, can not comfortably take care of a single board. Or if they did take care of it, because of the size of the board they would lack a proper view of the various parts of the system at all times which in case of emergency or trouble when full knowledge is particularly essential might prevent a proper carrying out of duties.

In consequence, we have seen developed the electrically operated dispatcher's boards, only multiplying the links in the chain. As a result of the sprawling design of the primary switchboard, we have come to a control board to integrate the primary board and to place the fundamentals in connection with its control in a sufficiently small space to be fully controlled by the operator in charge. That this has meant an economically wasteful development in two directions is apparent.

II. Modernizing Fundamentals

It was recognized that in order to get away from this

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

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cumbersome arrangement of switchboards, and provide a board on which all necessary instruments and control switches could be placed so that they would be entirely in view and under the hand of one operator, it would be necessary to develop a complete new line of small meters and small control equipment. Accordingly, the problem was attacked from this angle and a great deal of work was done in the development of such

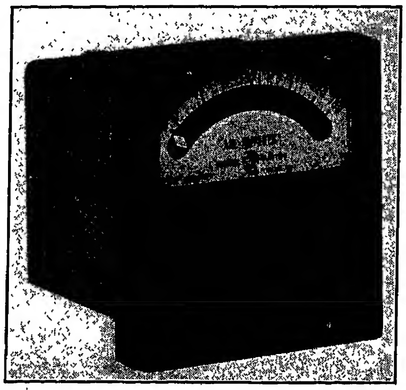


Fig. 1—A-c. Ammeter for Miniature Switchboard

meters, control switches, and indicating devices. This miniature equipment has been designed to be mounted on very small panels, and the resulting miniature board is capable of doing everything that could be done with the conventional but larger sized switchboard equipment.

Instrument elements have been developed for a-c. or d-c. ammeters, voltmeters, and wattmeters and kv-a. meters, which can be mounted in a standard case

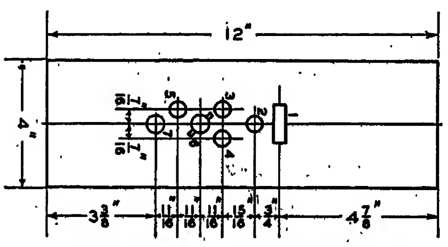


Fig. 2—Panel Showing

1. Card holder
2. Synchronizing receptacle
3. Green lamp
4. Red lamp
5. White lamp
6. Control switch
7. Operating key

having a front 4 in. wide by 4½ in. high and a body approximately 3½ in. square and from 6 to 10 in. deep. The scales on these meters are approximately 3½ in. long and are white with black markings. The needle pointer is furnished with a black tip. The front of this meter is drilled at each corner and supports the whole meter, thus allowing of direct mounting, with four machine screws. The volt-ampere burden for these instrument elements is in general somewhat lower than for the standard instrument elements. Fig. 1 shows a photograph of one of these instruments.

The control equipment and indications are taken care of by the use of a red light, a green light, and a white light, a control switch, a synchronizing receptacle, and an operating key or push button. The control switch itself is a development of the control switch used on supervisory equipments. The equipment is so wired that to close the circuit, the control switch is placed in the closed position, thereby closing a contact which is in series with a contact of the synchronizing receptacle and the operating key. When the operating key is depressed, the closing circuit is energized. The tripping is taken care of by placing the control switch in the open position in which position its tripping contact is wired through the operating key so that when the key is depressed, the oil circuit breaker is tripped. Fig. 2 shows a panel on which this equipment is mounted and an elementary wiring diagram may be seen in Fig. 3.

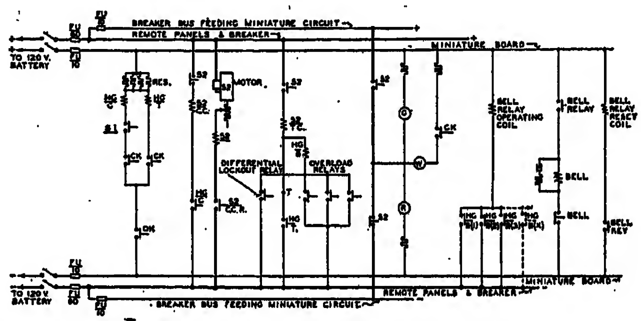


Fig. 3—Schematic Diagram for Typical Panel Showing Breaker Wiring

1. $\frac{H\ G}{C}$ Interposing closing relay
2. $\frac{H\ G}{T}$ Interposing tripping relay
3. $\frac{H\ G}{B}$ Series alarm relay in trip circuit
4. *S I* Synchronizing receptacle
5. *C K* Control switch
6. *O K* Operating key
7. *C C R* Control contactor
8. *T C* Trip coil

However, in connection with this control switch it has been necessary so far to use two interposing relays; one to handle the closing current, and one to handle the tripping current for the oil circuit breaker. A new control switch is being developed with adequate contact capacity so that the interposing relays will not be necessary. The interposing relay is a small instantaneous circuit-closing relay. The synchronizing receptacle consists of a telephone type jack and the wiring is shown in the elementary diagram of Fig. 3 and the arrangement of contacts as in Fig. 4.

III. Assembly

The development of these instruments, control switches, indicating lamps, and other devices has resulted in a new type of switchboard structure. This structure is fabricated from electrically welded steel plates. The two forms which have been developed, so

far, consist in one case of an upright rectangular cabinet fitted with a desk top extending from the panels at a height of about 30 in. from the floor, and in the other, of a number of individual sections which bolt together

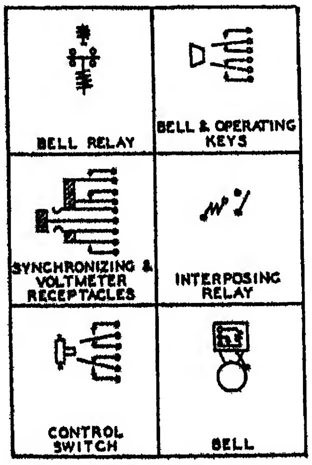


Fig. 4—Details of Switches and Relays

to form a polygonal arrangement with the switchboard on the inner side, attached to which is a desk top similar to that for the other design. This latter type, providing for the development of the panels on a circle, makes it possible to assemble a number of panels in such a position that they can be more easily observed and controlled.

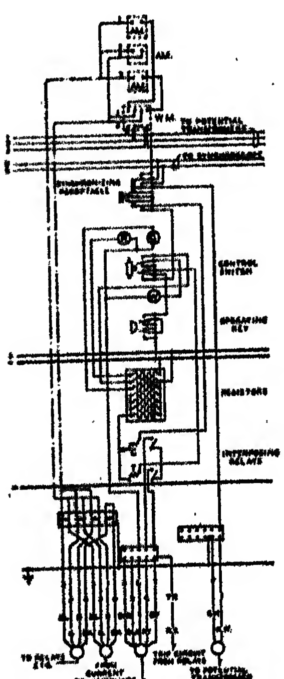


Fig. 5—Back View, Wiring Diagram of a Typical Feeder Panel

For both types of switchboard structure, the mounting is taken care of by cutting out sections from the steel fronts and providing frames to which the meters can be bolted directly. To this frame may also be bolted suitable small panels with the control switches, synchronizing receptacles, etc., mounted on them. A typical panel consists of the proper indicating instruments, control switch, indicating lamps, synchronizing receptacle, and operating key, etc., mounted vertically so that panel sections and meters are all flush. A wiring diagram is shown in Fig. 5 covering a typical panel. The arrangement can be seen from Figs. 6 and 7, which are the photographs of two designs. Fig. 8 shows a plan view of a typical section for the polygonal arrangement, also a side and front elevation and Fig. 9 shows the method of grouping the sections.

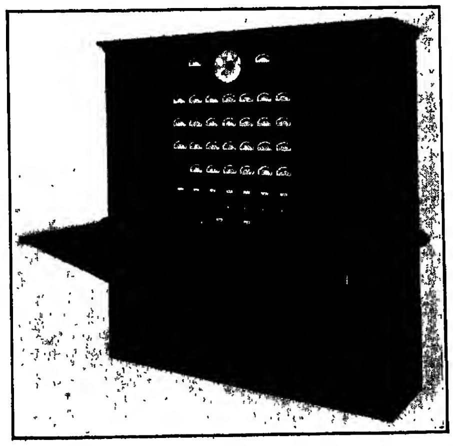


Fig. 6—Illustration of Rectangular Cabinet Type Switchboard

IV. Design Developments

Figs. 10 and 11 show two switchboards, Fig. 10 being a close-up view of the instrument and control section of an installation made at the Beaver Creek substation of the Kentucky and West Virginia Power Company and Fig. 11 a photograph of the board to be installed at the 132-kv. Zanesville substation of the Ohio Power Company, both of which companies are subsidiaries of the American Gas and Electric Company. From Fig. 11, which is a three-quarter view

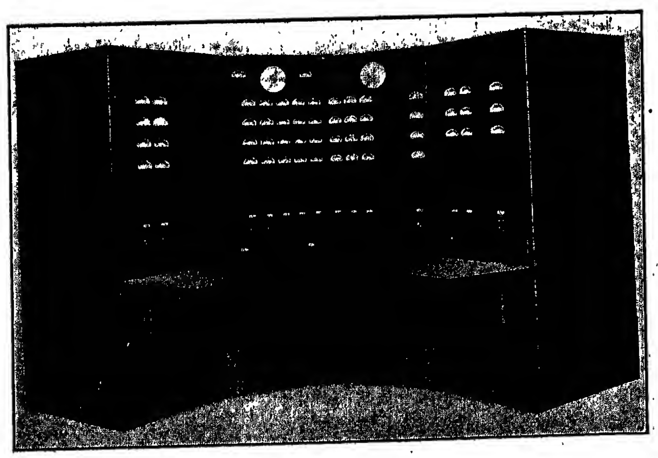


Fig. 7—Photograph of Multi-Unit Type Polygonally Arranged Switchboard

of the Zanesville board, it is evident how such a switchboard lends itself to complete supervision and ease of operation. The operator, from a swivel chair, can see all the instruments on the complete board and can easily reach all the control switches. The board shown in Fig. 11 consists of four sections, totaling 24 circuits. Such a board can be expanded to eleven sections, as shown in Fig. 9; and 66 circuits can be controlled just as readily.

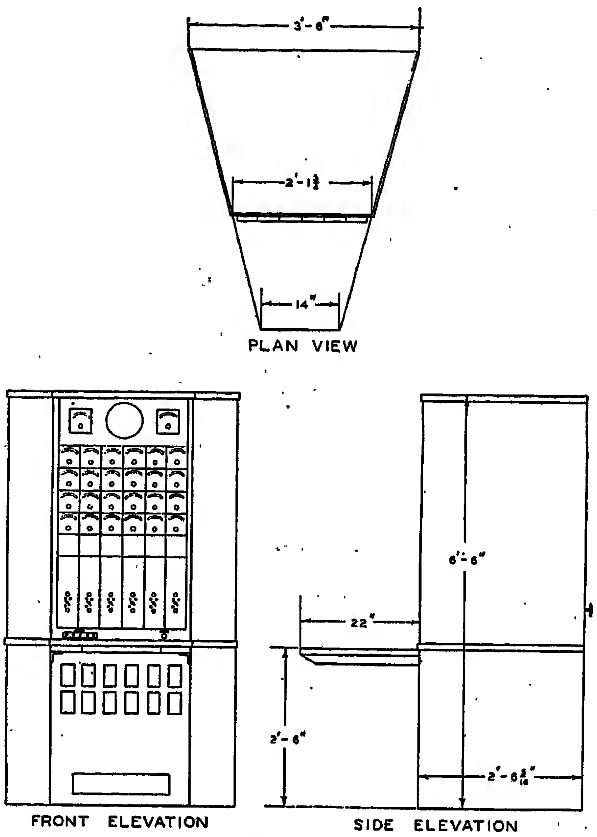


Fig. 8—Typical Unit for Zanesville 132-Kv. Substation Switchboard

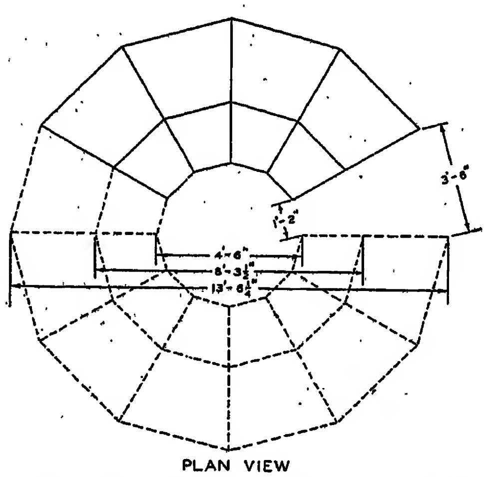


Fig. 9—Extent of Possible Development of Multi-Unit Board

V. Advantages

The advantages of the switchboard development described are almost self-apparent, but it may be well to summarize them here. They are:

1. *Compactness.* A board has been provided which takes up a small amount of space, certainly much less space than any other board heretofore developed attempting to accomplish the same functions.

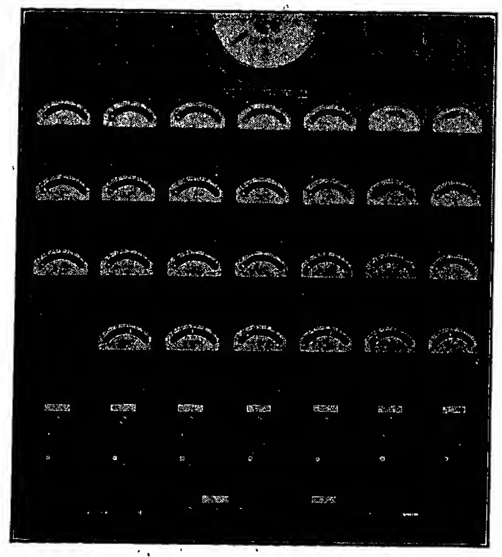
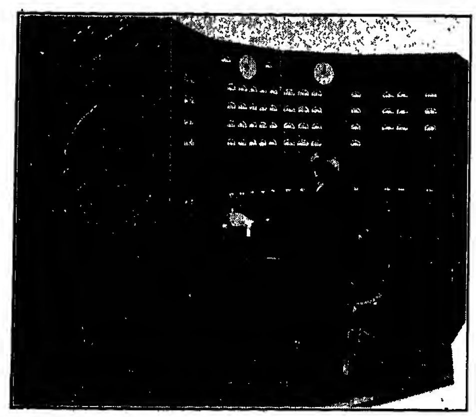


Fig. 10—Close Up View of the Instrument and Control Section of the Miniature Board Installed at Beaver Creek

2. *Ease of Operation.* As a natural concomitant, this compactness brings with it ease of operation. With no difficulty whatsoever a single operator can supervise the operation of 60 or more feeders and do so with a minimum amount of effort and a maximum amount of dispatch; further, due to the type of control switches employed, he can do this all while carrying on a telephone conversation or either giving or receiving instructions.



Fif. 11—Three Quarter View of Zanesville Switchboard Showing Ease with which It Can be Supervised

3. *Closer Supervision.* The small physical dimensions make it possible for the man actually operating the switchboard to exercise a closer degree of supervi-

sion; to know at a glance what has happened over the entire system supervised, and do so more easily than heretofore, without the intervention of other intermediate equipment. Besides, it saves the expense and complications of such additional equipment.

4. Ease of Erection. The board lends itself more readily than any other type of board to complete erection at the shop of the manufacturer and shipment complete as a unit. This makes it possible to install it more quickly and with less expense than a board which has to be disassembled or broken up into parts before shipment.

5. Good Appearance. By no means a negligible point in the favor of the new development is its excellent appearance. It cannot be claimed that most of the boards that have been built within the past decade or so have had beauty of appearance as their strong point; the new board most decidedly is a great advance in that direction.

6. Modernization. The advantages may be summarized in brief, as follows: The board is a definite step in modernization of an item of station and substation equipment that has too long been left to accumulate tradition and that has too long followed along old and weather-beaten paths. It is believed that the step taken at the present time will be helpful in the direction of further development and progress toward the modernization of an important item in electric plant and substation operation.

Acknowledgment is due to the switchboard engineers of the General Electric Company, who obviously did all the instrument and most of the other development work, and particularly to Mr. Chester Lichtenberg, without whose sympathetic cooperation this development would have been impossible. The author also wishes to acknowledge the help he received from Messrs. H. E. Turner and R. C. Miller, in the preparation of this paper.

Discussion

R. M. Stanley: If a power station should be built according to the general practise of the past, with complete switchboard control equipment and, in addition, should there also be included supervisory automatic control, the resulting cost would, of course, be greater and, therefore, the use of automatic or supervisory control would be questionable, even though many of the advantages of such control were realized.

If, however, departures from conventional general design can be accomplished successfully and ways found to include automatic and supervisory control at no greater cost or, perhaps, considerably lower cost, their adoption can be justified. At Louisville, Kentucky, in the Louisville hydro plant built during 1926 and 1927, the following was accomplished:

It was found possible by the adoption of a miniature switchboard to eliminate from this station the following elements which would have been used if fairly modern standards of design and engineering had been followed;

1. A slate or steel benchboard controlling generators, exciters, power transformers and station auxiliary.
2. A vertical slate or steel switchboard containing watthour meters, relays, etc.
3. A control room of dimensions approximating 60 ft. long, 18 to 20 ft. wide and 10 to 12 ft. high.
4. Suitable foundations, concrete or structural work, for a portion of a power-house building of the size outlined.
5. Control wiring, conduits, shelving, lead covered control cable or other suitable means for connecting the control and relay switchboard with the apparatus to be controlled.
6. Suitable lighting, by electric illumination or by skylights, windows, etc., for the control room and suitable ventilation and heating for the comfort of the operators.

Unit control of generators and power transformers, by means of control cubicles located nearby, permitted a saving in building and control conduit and wiring. Without some centralized equipment, station operators would be obliged to walk the entire length of the plant many times daily. Centralized control—necessary in such a large plant—was accomplished by the use of a supervisory control cabinet or miniature switchboard, small in size and cost and requiring little space in the building, located near the middle of the generator room.

At the cubicles, voltage reduced by instrument transformers to about 10 volts, and currents reduced to about ¼ ampere, permit the use of 16-pair lead-covered telephone cable between control cabinet and each generator cubicle. These telephone cables are installed in 1¼-in. conduit and the combined cost is about 80 cents per ft. installed. One three-conductor control cable, ordinarily used between control switchboard and generator equipment, installed in 1¼-in. conduit, costs about the same per ft. The 16-pair cable does the same work as that of 16 control cables and conduits ordinarily used between a switchboard and generator equipment, and the saving should, therefore, be apparent.

These savings in control wiring and conduit more than offset the cost of extra automatic and supervisory equipment so that with building costs considered, the total plant cost was reduced very materially.

To generalize a little; automatic equipments have been applied to small apparatus to start when required, or to connect groups of small equipment to power supply when this supply has been restored after interruption. There now seems to be no reason why such equipment cannot be applied and devoted to the task of restoring power supply for various parts of a system and to keeping generating equipment operating, ready to be re-connected to the load in the shortest possible time.

When system troubles occur, operators often are at a loss to know what to do. System troubles cannot be instantly diagnosed and remedies cannot be instantly decided on. Oftentimes before the trouble can be analyzed the opportunity for action to correct conditions has passed. These things should be worked out in a deliberate manner, and remedial measures planned in advance. As we gain in experience in operating our systems, we can predict more closely what is going to happen, anticipate conditions, and be prepared to handle a situation within the very short interval of time which is allowed us, and the automatic equipment affords a medium to do this.

We have known a great many things about this sort of equipment but have not, until recently, realized much about how ready it stands to help us operate our systems if intelligently applied.

We have thought that its extra cost must necessarily preclude its use, but in this we have been wrong. It has, and probably will, if properly and intelligently applied—afforded a means of reducing costs. Our application in the Louisville hydro plant has, I believe, demonstrated the entire practicability of handling, automatically, large sized units in a large station and this, in connection with a system which is of average size combines all of the transmission, distribution and generating problems met with on representative power systems of today.

As to sturdiness and durability, the cubicles contain all of the standard switchboard indicating and recording instruments required for ordinary station records, and also contain relays

and automatic control contactors and other equipment. Between these cubicles and the generators, transformers are installed; standard current and potential and oil circuit-breakers control cable in iron conduit. There is, therefore, a complete and separate system of control in each case.

Superimposed upon this system is a miniature system operating at 10 volts and ¼ ampere, but entirely separated by current and potential transformers and relays respectively so that any breakdown of any part of one system cannot affect adversely the operation of the other. If the miniature system of one unit fails the unit can be operated from the cubicle. This has not yet been necessary and two and one-half years' use of this plant has apparently justified our selection and adoption of these ideas and methods.

In addition to reduction of fixed charges due to reduced installation and construction costs, operating costs are greatly reduced. Two men per shift operate the entire plant except when extra help is required on the outside at the racks where trash or ice accumulate.

C. Lichtenberg: Automatic supervisory systems have introduced smaller control devices and connecting wires into the power field. They have permitted a greater concentration of control equipment and have enabled more units to be placed conveniently under the control of a single supervisor. They have brought forth the so-called miniature switchboard.

A miniature switchboard may be defined as a small or concentrated switchboard using supervisory lamps and keys and small sized instruments. The lamps with their color caps are used to give indications of the positions of the devices controlled. The keys replace the conventional control switches. They control the operation of remote electrical devices through auxiliary relays and they may in time be replaced by miniature control switches. These will combine the present control keys and auxiliary relays without, however, appreciably increasing the space occupied on the panels. The instruments are of conventional design but with restricted scale length. This permits using conventional switchboard instrument accuracy with small size cases.

The adoption of the miniature switchboard permits radical changes in the design of stations and substations. It permits the elimination of the switchboard gallery as such, reduces conduit runs to a minimum and renders pull boxes unnecessary. It reduces the space requirements of a switchboard and its connections, and permits a marked simplification in station design. The switchboard will now contain only the control keys, or miniature switches, and a minimum number of instruments. Consequently, it will be very much smaller than the conventional switchboard. It will approximately require only about one-tenth the space of a conventional design of switchboard and will permit a very much more convenient operation of the units. It will permit the supervisor to maintain telephone communication with some remote point while at the same time reading instruments or operating devices in a maximum of 60 to 66 circuits.

The connections from the miniature switchboard to the remote electrical devices may be most conveniently made through conventional telephone cables. For greater safety it is recommended that the same standard of insulation be adopted as has been standardized by the American Railway Association for railway telephone and telegraph cables. The use of such cable with No. 19 B & S copper conductor is possible since the lamps and keys and the new miniature control switches are designed for 24-volt, 48-volt, or 60-volt operation. The miniature instruments may be obtained with 60-volt and 0.5-ampere windings. Consequently, lead covered cable without conduits may be installed between the miniature switchboard and the remote electrical devices. This markedly reduces the expense of control cable and conduits and permits greater flexibility in the location of the miniature switchboard and of the connections.

Besides marked reduction in installation cost, miniature switchboards have increased operating ease and testing facilities.

These boards are designed, as indicated in Mr. Sporn's paper, that they may be placed in circular formation. A maximum of 10 or 11 of these units may be placed in one group. This will give a seated individual the control of a maximum of 60 to 66 circuits. The circuits may be the control of individual oil circuit breakers or they may be the control of a complete hydroelectric unit as in the Louisville automatic hydroelectric station described by Mr. R. M. Stanley.

Many combinations of miniature switchboards will suggest themselves to designers. For example, one arrangement is the use of six-unit groups representing 180 deg. of a circle. These will take care of 36 circuits or of 36 machines. Six of such grouping arranged in two parallel lines with the concave sides facing each other may readily be used to control the largest station contemplated today. Such an equipment could easily be placed in a room or space about 35 ft. wide and 80 ft. long and still give ample room for the operators or supervisor.

The latest designs of miniature switchboards as exemplified in Mr. Sporn's paper indicate that the development is progressing rapidly and that today designs are available to meet most all conditions arising in stations and in substations. These designs should do much to reduce the cost of electricity supply undertakings and operation.

H. B. Wood: In the paper on miniature switchboards, the author has emphasized the desirability of simplifying the control board. This is especially helpful in minimizing operating errors.

The comparison of the miniature board with the ordinary type of control is not placed on an equal basis as the author has neglected to mention the space required for the relays, watthour meters, signal devices and other control apparatus.

To prevent operating errors, it is just as necessary to obtain circuit segregation on the board as in the bus and switching structures. A plan view of a miniature board is shown in the paper intended to provide for 66 circuits. With such a mass of identical devices the optical and mental grasp of the operator is exceeded and the identity of highly important equipment is lost and mistakes are apt to occur.

The control room should be simplified as much as possible, bringing to the board only the important features. Relays if mounted close to the instrument transformers will save a large amount of conduit and wire. Watthour meters, temperature recorders and curve drawing meters can be located elsewhere. Automatic devices have been developed to remove many duties from the switchboard operator.

In the miniature switchboards, devices of the telephone type are used. These devices including as they do added auxiliary relays are not sufficiently substantial or dependable for use in large high capacity plants. We need safer and more sturdy control equipment not reduced clearances and insulation.

Philip Sporn: Mr. Stanley discusses particularly the experience obtained with the control scheme used for the Louisville hydro plant of the Louisville Gas and Electric Company. The problem which confronted the designers on this particular job was one of providing centralized control with a minimum of space required and at a cost less than for the usual type of installation. This problem was solved by providing individual boards at each unit and by the use of a supervisory type board on which was grouped the control for all units. The solution as applied to the Louisville hydro plant, of course, is not strictly speaking a miniature switchboard application. The miniature board embodies a number of ideas developed in the Louisville hydro plant board but the development was carried in another direction and a great deal further.

The use of automatic equipment to minimize operating errors in times of emergency which Mr. Stanley suggested, has interest-

ing possibilities, but this too is out of the province of miniature switchboards as covered in this paper.

Mr. Lichtenberg's discussion constitutes in brief a description of what a miniature board really is.

Mr. Wood's discussion, I believe, comes the nearest to actual criticism of the ability of the board to perform what it is intended to do.

It seems to me that the thing which should not be lost sight of is the fact that the miniature board is really nothing more or less than a standard large sized control board greatly reduced in size. The mere fact that the board is small and that some of the devices on it have been the outgrowth of the development of supervisory control boards, as pointed out by Mr. Wood, does not mean that any part of this miniature board is less reliable than a corresponding part of a standard board.

The only additional devices in the control circuits are the auxiliary relays which are used. These are very simple, take up little room and are very positive in operation. Even these, however, we expect to be able to eliminate in the near future by using complete miniature control switches as mentioned by Mr. Lichtenberg in his discussion and also in the paper itself.

The fact that indicating and integrating meters and other indicating and recording devices are not mounted on the miniature control board does not detract at all from its value since it has been common practise for some time to use independent metering and control boards. It is even quite possible, in case it should be desired, to mount the necessary metering devices in the back of the miniature board units especially in the case of the circular arrangement where there is a considerable amount of extra room available. In connection with this it seems to me that one of the big problems facing instrument designers at the present time is that of reducing the size of indicating and integrating meters and of relays to meet a demand which is continually increasing for smaller devices of this kind. There is too, I believe, no real reason why these classes of devices cannot be reduced in size without any sacrifice in efficiency if the problem is approached seriously by the designers.

I do not believe that Mr. Wood's criticism concerning the probability of making mistakes by using the miniature board, where a large number of circuits is involved, is one that will be substantiated in actual practise. I believe that there is a much greater likelihood of mistakes occurring where an operator has to watch extensive control boards of the present type than there is where everything comes under his hand and eye as in the case of the miniature boards.

The grouping of circuits on the miniature boards can also be made extremely simple. For those who prefer to use a mimic bus, especially for boards used to control generating stations, this modification can be applied to the miniature board. Adequate communication systems for keeping an operator in touch with the boiler and turbine rooms can also be developed in miniature.

There is a great deal to be said as Mr. Wood points out for designing control equipment for sturdiness, but this does not mean, as has been so generally supposed in the past, large cumbersome boards with correspondingly large and ungainly devices mounted on them.

Concerning the reduction of clearances and insulation, there is certainly no reason why insulation and clearances as provided on these old style boards cannot be cut down. When the problem is attacked intelligently, proper insulation can be provided with considerably reduced clearances over those which have been used in the past. The tendency in general in control work, I believe, is going to be more and more toward the use of miniature equipment with the large savings which can be effected in reduction of space required to house such control, in the number of operators which it will be necessary to employ to adequately supervise any particular installation, and in the reduced cost of equipment itself which is going to become more and more apparent with the development of such miniature equipment.

Mutual Impedances of Ground-Return Circuits

Some Experimental Studies

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Synopsis.—This paper describes some of the results of the work of the Joint Development and Research Subcommittee of the National Electric Light Association and Bell Telephone System on the mutual impedances of ground-return circuits.

The first part of the paper deals with some experiments which were performed to establish an experimental background for the testing of theoretical ideas. Different theories, one involving an "equivalent ground-plane," a second a d-c. distribution in the earth, and a third an a-c. distribution in the earth, are discussed in the light of the experimental results. While none of these is adequate to explain all the observed phenomena, each has a field in which it can be made useful.

The second part of the paper is devoted to a description of practical means for predetermining the mutual impedances of power and telephone lines. This involves an experimental determination of a curve of mutual impedance as a function of separation in the region of the proposed exposure and the calculation of the over-all mutual impedance between the proposed lines from this curve and the dimensions of the exposure. The results of trials of this method in two locations are given which indicate that it should be of sufficient accuracy for engineering purposes.

* * * * *

INTRODUCTION

THE magnitude of the inductive coupling between power and telephone lines is a factor of fundamental importance in problems of coordination to prevent interference between these two classes of lines. Accordingly, this is one of the subjects under investigation by project committees of the Joint Committee on Development and Research of the National Electric Light Association and the Bell Telephone System. It is the purpose of this paper to present the results of some work which has been done under the auspices of the Committee on one phase of this problem, namely, the mutual impedance of ground-return circuits.

The mutual impedance of two ground-return circuits is determined by measuring the ground-return current in one circuit (the "disturbing" circuit) and the open-circuit voltage at the terminals of the second circuit (the "disturbed" circuit). The vector ratio of the open-circuit voltage to the ground-return current is then defined as the mutual impedance of the two circuits.

For any normal or abnormal operating condition of a power system, the currents, either at fundamental frequency or at any harmonic frequency, in any of the lines can be resolved into components, some of which are entirely confined to the wires while another component flows in a circuit composed of all the wires as one side with the ground as a return path. The work which is described in this paper deals with the magnitude of the induced voltages on exposed telephone lines caused by the latter component. It has been directed to two ends, first, the establishment of an experimental basis for the study of the physical factors involved in the inductive coupling of ground-return circuits, and second, the development of practical methods to enable the advance calculation of the mutual impedances of power and telephone lines. The work is accordingly presented in two parts; first are given the results of tests made at a field laboratory in which testing conditions could be controlled, and second, tests in which the practical side of the problem was investigated are described.

CROSS KEYS TESTS AND THEORETICAL BACKGROUND

Cross Keys Tests. An extended series of measurements was made at a field laboratory operated by the subcommittee near Cross Keys, New Jersey, about 20 miles southeast of Camden. A single conductor, located about 34 ft. above the ground and 8500 ft. in length, was available for the disturbing circuit. For disturbed circuits, 500-ft. lengths of insulated wire were laid on the earth parallel to the disturbing conductor, at several separations, as shown on Fig. 1. Grounds were provided at the ends of each line. Ground-return current was transmitted over the disturbing line at 60 cycles from a commercial source, or at frequencies between 100 and 1000 cycles from a vacuum-tube oscillator with power amplifier. The measuring instrument was an a-c. potentiometer, equipped with suitable filters so that the observations

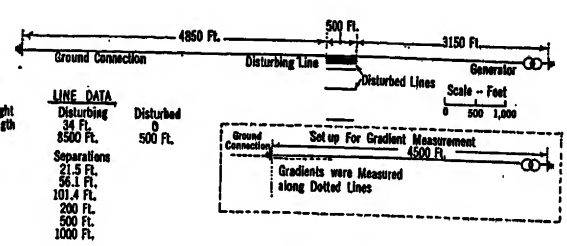

FIG. 1—CROSS KEYS TESTS. EXPERIMENTAL SETUP

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

were unaffected by the presence of harmonics in the disturbing current.

At several frequencies within the range from 60 to 1000 cycles the current in the disturbing line, the open circuit induced voltage in each of the short ground-return circuits, and the phase angle between these two quantities, were measured. The mutual impedances were derived from the ratio of the induced voltage to

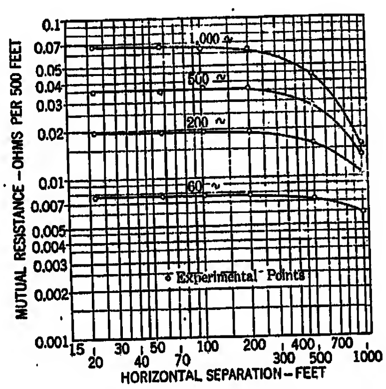

Fig. 2—Cross Keys Tests—Mutual Resistance

the inducing current, in accordance with the definition. The results of these tests are given on Figs. 2, 3, and 4. Fig. 2 shows the resistance components, Fig. 3 the reactance components, and Fig. 4 the magnitudes of the mutual impedances.

The measurements described above were made with the object of investigating the mutual impedances of ground-return circuits in which the ground connections

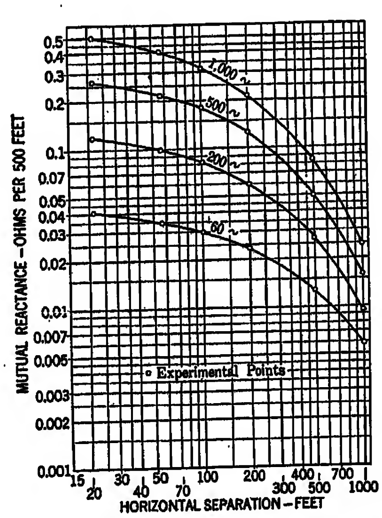

Fig. 3—Cross Keys Tests—Mutual Reactance

on the disturbing line are sufficiently removed from those on the disturbed circuit so that effects due to proximity of the grounds may be ignored. The results presented above were supplemented by observations demonstrating that the induced voltage in a parallel circuit was closely proportional to the length of the circuit and that the voltage induced in a ground-return circuit extending perpendicular to the disturbing line was exceedingly small.

As the points of grounding on the disturbed circuits approached those of the disturbing circuit this proportionality no longer existed nor was the voltage in a perpendicular circuit of negligible magnitude. A second series of tests was therefore conducted to determine the nature of this effect and the area in which it was of importance.

In these tests voltages were measured in very short disturbed circuits extended along radii converging on one of the ground electrodes on the disturbing line. At each location the circuit was made progressively shorter until the quantity measured per unit length was practically independent of the length. Thus the gradient of the mutual impedance, in the direction of the radius at the point of measurement was determined. These measurements were made only at a frequency of 60 cycles.

The resulting observations are shown in Figs. 5 and

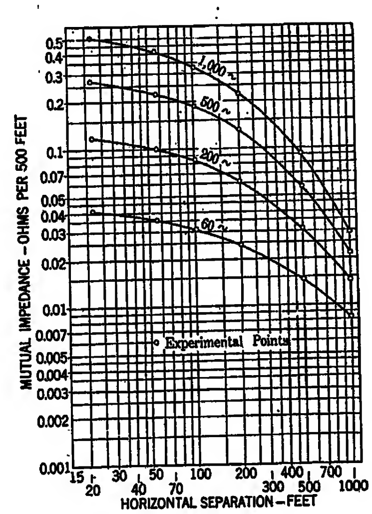

Fig. 4—Cross Keys Tests—Mutual Impedance

6. Fig. 5 shows the magnitude of the mutual impedance gradient along three radii, one radius being directly under the disturbing line, the second perpendicular to it, and the third along the extension of the line. Fig. 6 shows the corresponding phase angles. Under the disturbing line, as the distance from the grounding point is increased, the gradient approaches a constant value and the phase angle changes rapidly from a very small value to an angle approaching 80 degrees. Along the latter two radii, however, the magnitude of the gradient appears to decrease indefinitely and the phase angles are smaller.

A more complete analysis of the results of both groups of tests is given in connection with the discussion of theory which follows:

Equivalent Ground-Plane Theory. The equivalent ground-plane method of computing the mutual impedances of ground-return circuits utilizes a very simple

formula and has been in common use for a number of years. A derivation and discussion of the formula together with some experimental results are given in the report published by the California Railroad Commission in 1919.[1]

This method assumes that the returning earth current may be considered as flowing in a hypothetical plane surface of perfect conductivity located some distance below the actual surface of the earth. This surface is usually termed the "equivalent ground-plane." The

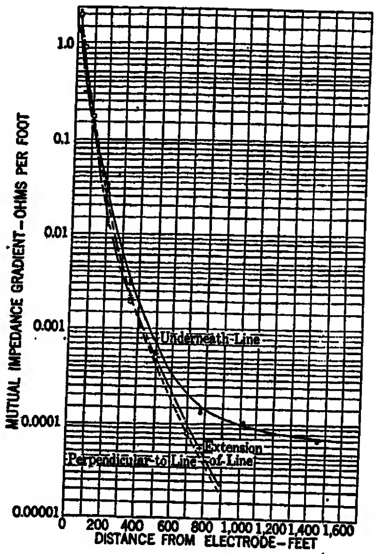

FIG. 5—CROSS KEYS TESTS—MUTUAL IMPEDANCE

Gradient in vicinity of grounding electrode. Experimental curves

depth of the equivalent ground-plane below the actual surface of the earth varies in different locations from about 50 ft. to 5000 ft. or more, depending upon the character and resistivity of the earth and the frequency.

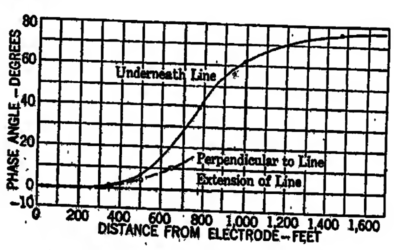

FIG. 6—CROSS KEYS TESTS.

Phase angle of mutual impedance gradient in vicinity of grounding electrode. Experimental curves

This method is subject to the objection that it fails to represent completely the observed phenomena. For instance, the method represents the mutual impedance only with a reactive term, while the experimental results indicated a substantial resistance component, particularly at the wider separations and higher frequencies. Furthermore, no attempt is made to explain the phenomena observed in the neighborhood of the ground electrodes. However, in one respect the theory leads to results comparable to those observed; the magnitudes of the mutual impedances as observed under conditions in which end effects are negligible can be checked reasonably well with a suitable choice of ground-plane. Comparisons demonstrating this point are made on Fig. 7, where it will be seen that the curve of experimental mutual impedance for a frequency of 60 cycles can be fitted very well by a calculated curve with a ground-plane depth of 835 ft. That the depth of the equivalent ground-plane depends on the frequency is seen from the fact that to fit the experimental curve at 500 cycles requires the use of a ground-plane depth of 385 ft.

Method Assuming D-C. Distribution in the Earth. For an earth of uniform conductivity, the distribution of the current in the earth for a ground-return circuit energized from a d-c. source has been employed by

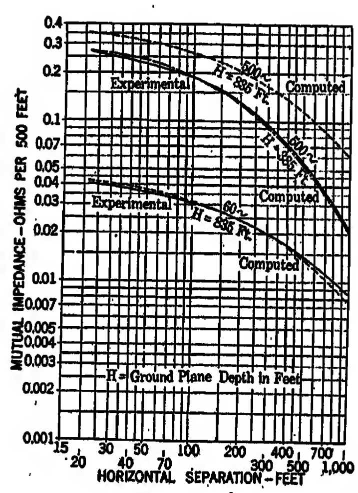

FIG. 7—CROSS KEYS TESTS GROUND PLANE THEORY

Comparison of measured and calculated values of mutual impedance

G. A. Campbell[2] to derive formulas for the mutual resistance and inductance of ground-return circuits. The mutual resistance is expressed by a very simple formula which involves only the earth resistivity and the distances between the points of ground connection on the disturbing and disturbed circuits. For the calculation of the mutual inductance formulas and graphs requiring only a knowledge of the mutual arrangement of the wire parts of the disturbing and disturbed circuits with respect to each other and the earth are given. The mutual inductance is independent of earth resistivity. While these formulas are, of course, strictly applicable only for direct currents, it is to be expected that at sufficiently low frequencies the ground-current distribution would not differ appreciably from that for direct current, and hence for these frequencies, the calculated d-c. mutual resistance and inductance should approximate the actual values. In the paper re-

1. For references see Bibliography.

ferred to, some experimental results at frequencies of 25 and 60 cycles supporting this point of view are presented.

The experimental curves of Fig. 2, which were obtained from measurements at Cross Keys on the 500-ft. disturbed lines near the middle of the 8500-ft. disturbing line, indicate a pronounced increase in

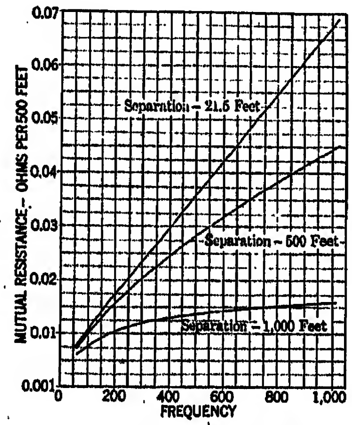

FIG. 8—CROSS KEYS TESTS

Variation in mutual resistance with frequency and separation

mutual resistance with increase in frequency in the range from 60 to 1000 cycles. These results have been replotted on Fig. 8, and it is apparent that for separations within the range of 20 to 500 ft. the mutual resistance increases rapidly in almost linear relation to the frequency. For the frequency range and circuit lengths involved in this series of tests, it would appear that a formula for the mutual resistance, based on a d-c. distribution in the earth, is inadequate.

The mutual-inductance curve of Fig. 9 has been com-

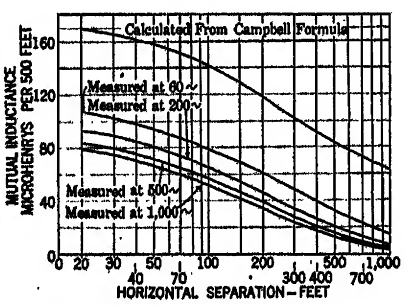

FIG. 9—CROSS KEYS TESTS

Campbell theory comparison of measured and calculated mutual inductances

puted according to the formulas given by Campbell, and for comparison purposes the mutual inductances derived from the mutual reactances shown on Fig. 3 are also plotted. It will be seen that the observed mutual inductances decrease as the frequency is increased, and that while the trend of the observed values is towards agreement with the calculated values as the frequency is decreased, the agreement is far from good at 60 cycles, the lowest frequency used in these tests.

In the immediate vicinity of the grounding electrode on the disturbing circuit, however, the experimental observations of mutual impedance gradient can be explained fairly well in terms of a d-c. distribution. The curves of Figs. 5 and 6 show that in the immediate neighborhood of the electrode, the gradient along any radius diverging from the electrode decreases very rapidly with increase in distance from the electrode, and is approximately in phase with the current. The gradient along the radius under the disturbing line approaches asymptotically a constant value, and

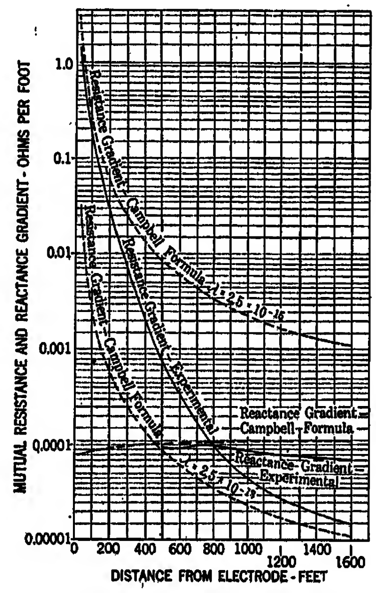

FIG. 10—CROSS KEYS TESTS

Mutual impedance gradient in vicinity of grounding electrode. Comparison with calculated values

beyond 300 ft. from the electrode the phase angle changes rapidly from a very small value to a value approximating 80 deg. The gradient along the other radii, however, appears to decrease indefinitely

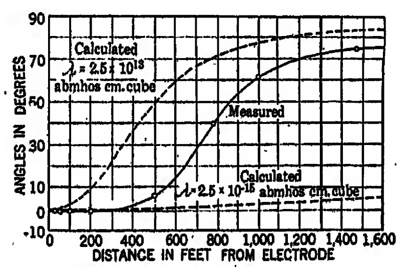

FIG. 11—CROSS KEYS TESTS

Comparison of measured and calculated (from Campbell's formula) angles of mutual impedance gradient

and the phase angles are smaller. Such effects are in qualitative accord with predictions based on a d-c. distribution, as will be seen by reference to Figs. 10 and 11.

On Fig. 10 are plotted the resistance and reactance components of the observed gradient under the disturbing line, with values computed using Campbell's

formulas. Two calculated curves for the resistance component are plotted, for conductivities of 2.5×10^{-15} and 2.5×10^{-13} (abmhos per cm. cube). It will be seen that the experimental values lie between these two curves, tending towards the former for short distances from the electrode and towards the latter for long distances. As in the measurements previously described, the calculated mutual reactance component is greater than the measured value, although in this case the discrepancy is substantially smaller. On Fig. 11 are shown the phase angles of the gradient as computed from the calculated values of resistance and reactance components given on Fig. 10. Here also the measured curve falls between the two calculated curves.

Since the gradient near the electrode is obviously affected mainly by the conductivity of the earth in the immediate neighborhood, and that at remote points is influenced more by the conductivity of the earth at substantial depths, the possibility that the earth in this region is not homogeneous, but stratified, is suggested. These curves seem to support the conclusion that the earth in this neighborhood has at least two strata, the upper one having a very low conductivity and the lower one a conductivity approximately a hundred times greater. Further experimental evidence tending to the same conclusion has been obtained, and will be described presently. For the present it may be pointed out that this conclusion is supported by the geological data pertaining to this region, for which an upper layer of sand and gravel from 130 to 170 ft. in depth is indicated, superimposed on a mixed structure of sand, clay, and shale, with a substantial amount of ground water.

Methods Considering A-C. Distribution of Earth Current. The problem of computing the mutual impedance of ground-return circuits, considering an a-c. distribution in the earth has been attacked by several writers.[3] In the interpretation of the experimental results, the papers of J. R. Carson[7] and F. Pollaczek[6] have been used, since a minimum of assumptions was made in the solutions advanced by these writers. The assumptions made are that the disturbing circuit is straight and of great length,[9] that the propagation constant, in absolute units, of the circuit is very small compared to unity, and also that the earth is a homogeneous body of fairly good conductivity. With these assumptions it is found possible to solve the fundamental field equations for the magnetic and electric fields in the vicinity of the disturbing conductor at points remote from the ends of the circuit and thence to get the mutual impedance. Physically, this method recognizes and takes into account the fact that in a conductor of large extent, such as the earth, the distribution of alternating current will be influenced by the changing magnetic field. Qualitatively, the effects are similar to those involved in the well-known skin effect, and may be thought of in terms of a distribution of eddy currents in the earth. It is obvious that the distribution of the eddy currents will depend on the earth conductivity and also on the frequency. The resultant fields, and hence the mutual impedances, will then be functions of earth conductivity and of frequency.

Presentation of the formulas and graphs giving the results of the analysis is outside the scope of the present paper, and reference should be made to the original papers for these. As an illustration of the results, however, the curves of Fig. 12 have been prepared, showing the calculated mutual resistance and reactance of ground-return circuits at a frequency of 60 cycles for

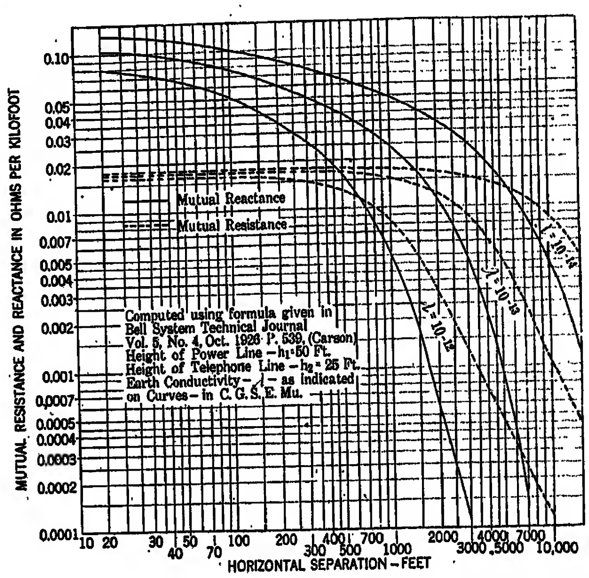

FIG. 12—RESISTANCE AND REACTANCE OF GROUND-RETURN CIRCUITS FREQUENCY 60 CYCLES

several values of earth conductivity, within the range of experimental values. Both the resistance and reactance components are seen to be pronouncedly affected by earth conductivity, particularly for the larger separations.

In applying this theory to the tests made at Cross Keys, the procedure adopted, in the absence of direct data on the earth conductivity at this location, was to choose an earth conductivity which would result in the best fit between the calculated and observed values, and to see whether a single value for earth conductivity would suffice to explain all the results. On Fig. 13 comparisons have been made between the experimentally determined mutual impedances for the 60-and 500-cycle frequencies; the curves were computed by use of the formulas given by Carson. It will be seen that in so far as the magnitude of the mutual impedance is concerned an excellent agreement can be made between the calculated and observed values. However, for the best agreement it is found necessary to assume a different earth conductivity

3. See bibliography references 3 to 9, inc.

at 500 cycles than at 60 cycles. Thus, while at 60 cycles the indicated earth conductivity is 4.2×10^{-13} abmhos per cm. cube, at 500 cycles it is 2.76×10^{-13}. However, a computed curve for 500 cycles, using a conductivity of 4.2×10^{-13} falls below the experimental curve by only 30 per cent. Table I gives the values of earth conductivity required to give the best fit to the curve of mutual impedance at each frequency. The range is not large, extending only from 4.2×10^{-13} at 60 cycles to 2.0×10^{-13} at 1000 cycles.

Turning to the components of the mutual impedance, however, the agreement is found to be not as good. Fig. 14 shows the measured values of mutual resistance and reactance at 60 cycles and at 500 cycles, also the computed values, the calculations at each frequency being made with the earth conductivity indicated in Table I. At 60 cycles the agreement is quite good, but at 500 cycles the departure between calculated and measured values is large. The measured mutual resistances are consistently lower than those calculated, while the measured mutual reactances are higher.

As indicated by the above comparisons, a theory of the kind under discussion leads to results which are in quite good quantitative agreement with the experimental results; it is of some interest to discover whether an extension of the theoretical ideas would lead to still closer agreement. It was stated previously that the measurements around the grounding electrode

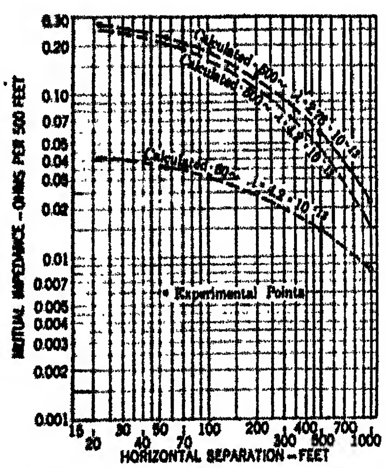

FIG. 13—CROSS KEYS TESTS—CARSON THEORY

Comparison between calculated and measured values of mutual impedance

could be accounted for on the hypothesis that the earth in this neighborhood is stratified, with a conductivity of around 2.5×10^{-15} near the surface and 2.5×10^{-13} in the lower depths. Qualitatively, it is to be expected that with such an earth structure the mutual resistance would be less, and the mutual reactance greater, than the corresponding values for an earth of uniform conductivity, since the eddy currents near the surface of the earth will be less, due to the lower earth conductivity.

Quantitatively, it would seem that a first approximation to the effect of a stratified earth in which the upper stratum has a much lower conductivity than that of the lower region could be obtained by assuming that the currents in the upper layer are negligible and hence that this layer can be abolished. The mutual impedances can then be worked out by the formulas applicable to a homogeneous earth, using the earth conductivity of the lower region and fictitious conductor heights, formed by adding the thickness of the upper stratum to the heights of the conductors above the actual earth's

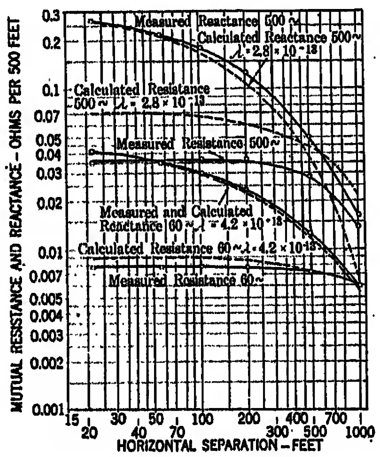

FIG. 14—CROSS KEYS TESTS—CARSON THEORY

Comparison between calculated and measured values of mutual resistance and reactance

surfaces. Preliminary calculations have been made using this scheme, and it was found that using a conductivity of 5.0×10^{-13} for the lower stratum and a thickness of 130 feet for the upper stratum an excellent

TABLE I
CROSS-KEYS TESTS
Earth Conductivity Giving Best Agreement Between Calculated and Measured Values of Mutual Impedance

Frequency cycles	Indicated earths conductivity from Carson's formulas abmhos per cm. cube
60	4.2×10^{-13}
200	3.75×10^{-13}
500	2.76×10^{-13}
1000	2.0×10^{-13}

agreement could be found between calculated and observed values for all frequencies. The agreement extended not only to the magnitudes of the mutual impedances, but to the components as well.

Because of the simplifying assumption that the disturbing circuit is so long that the effects due to the ground connections at its ends can be neglected, the theory which we have been discussing is obviously inadequate to explain the phenomena in the neighborhood of the grounding electrode.

PRACTICAL METHODS FOR PREDETERMINING COUPLING BETWEEN POWER AND TELEPHONE LINES

The ultimate purpose of the work of the committee is to develop simple methods to enable the calculation of

the mutual impedance between power and telephone circuits before they are built. It is evident from the foregoing discussion that the use of any formula for the mutual impedance of ground-return circuits requires a knowledge of the conductivity of the earth or of the depth of the equivalent ground-plane. In the relatively few places in which tests have been made, a range of earth conductivity from 10^{-12} to 10^{-14} abmhos per cm. cube has been observed, and reference to Fig. 12 indicates that within this range of earth conductivity a variation in mutual impedances of 20 to 1 or more may exist. Therefore, other experimental work has been done with the object of developing relatively simple testing schemes, the results of which could be used to predict the coupling coefficients in advance of the construction of the power or telephone line. An obvious method is to determine an experimental coupling curve by performing tests similar to those made at Cross Keys, using short-length disturbed circuits and either an existing power or telephone line, or a specially laid out conductor, as the disturbing line.

This experimental curve would then be used to compute the coupling between power and telephone lines. One advantage of using an experimentally determined coupling curve is that it obviates the necessity of knowing or assuming a structure and conductivity of the earth; the coupling curve can be used directly without reference to any theoretical formulas. To determine the practicability of such a scheme, 60-cycle tests have been made in two locations where existing exposures were present, for the purpose of determining

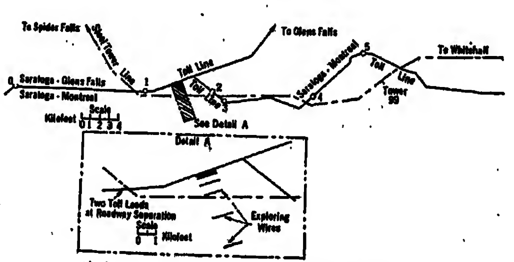

FIG. 15—GLENS FALLS TESTS

	Circuit arrangements	
Tower 99	3-Phase conductors	Grounded
Circuit	Power	Telephone
Height	50 ft.	20 ft.
Frequency	60 cycles	

the accuracy with which experimental observations could be predicted.

Tests at Glens Falls, N. Y. Fig. 15 shows the arrangement of circuits involved in tests made at Glens Falls, N. Y. A section of the Saratoga-Glens Falls telephone line about six miles in length was energized with ground-return current. Measurements were made of the voltages induced in short ground-return circuits laid on the ground parallel to the straight section of the telephone line. The resistance and reactance components of the mutual impedance derived from these measurements are given on Fig. 16. As a matter of interest the mutual resistance and reactance computed by the use of the Carson formulas for an earth conductivity of 1.75×10^{-12} are also given. This earth conductivity gives the best agreement between the calculated and observed magnitudes of the mutual impedances. The general agreement between the computed and observed quantities is much like that found from the Cross Keys tests.

Earth return current was then sent over the power line from Spier Falls to Tower 99, and induced voltages

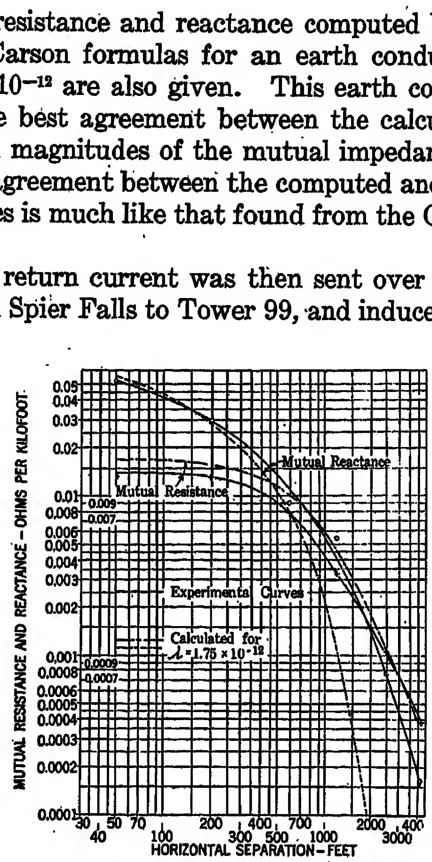

FIG. 16—GLENS FALLS TESTS

Experimental values of mutual resistance and reactance

measured in the entire exposed section of the Saratoga-Montreal telephone line, and in several parts of the exposure as indicated on the sketch. In Table II,

TABLE II

GLENS FALLS TESTS

Measured Mutual Impedances of Power and Telephone Circuits and Comparison with Values Calculated from Experimentally Determined Coupling Curves

Section of telephone line	Measured mutual impedance—ohms	Calculated mutual impedance—ohms
0–1	$0.0586 \angle 68.5°$	$0.0614 \angle 63.3°$
1–2	$0.0294 \angle 52.4°$	$0.0564 \angle 49.8°$
2–3	$0.0476 \angle 73.4°$	$0.0382 \angle 69.6°$
3–4	$0.107 \angle 56.4°$	$0.113 \angle 49.2°$
4–5	$0.100 \angle 44.4°$	$0.0117 \angle 35.8°$
0–5	$0.347 \angle 53.8°$	$0.267 \angle 55.3°$

the observed mutual impedances determined from this latter test are compared with values calculated by using the experimental coupling curve given on Fig. 16. The agreement between computed and observed values is, in general, only fair, although for two of the parts, the agreement is excellent. It is thought that the rather poor check for Sections 1-2 and 2-3 is due to the inductive effect of currents set up in the ground wire on another power line which extended through these sections. With regard to the extreme departure of the measured mutual impedance for Section 4-5 from that calculated it is impossible to decide the cause from the

experimental data available. A possible explanation is that it is due to a large difference in earth conductivity in this region from that in the region in which the coupling curve was determined. The large difference in this section is reflected in the rather poor check in the over-all coupling. (Section 0-5).

Tests at Masillon, Ohio. Tests made at Massillon, Ohio, were similar to those at Glens Falls, except that the arrangements were somewhat more elaborate.

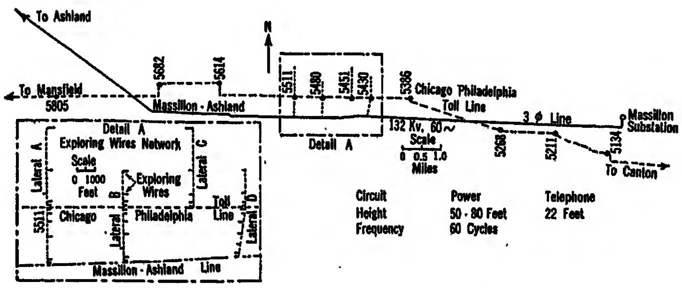

FIG. 17—MASSILLON TESTS—CIRCUIT ARRANGEMENTS

The layout of the circuits involved is shown in Fig. 17. The exposure is about 16 mi. long with separation between the power and telephone line ranging from a crossing to about 4200 ft., a large part of the exposure being at a separation of about 3000 ft. A set of "exploring wires," each 200 ft. in length, was laid on the ground parallel to the telephone line as shown in the detail of Fig. 17. These were arranged in four groups and were distributed over an area approximately 1½ by 2 mi. Coupling curves were determined from measurements of the voltage induced in the exploring wires for the condition of the telephone line energized with 6 amperes ground-return current, and also for the condition of the power line energized with 40 amperes ground-return current. The mutual impedances derived from the two sets of measurements are practically identical. Fig. 18 shows the resistive and reactive components of the coupling curve using the average of all measurements made on the exploring wires. A comparison of the measured curves with curves calculated by Carson's formulas for a value of earth conductivity of 3.6×10^{-13} abmhos per cm. cube show the same type of agreement as that observed at Cross Keys and Glens Falls.

The principal reason for using such a large number of exploring wires on this particular test was to investigate the effect of local irregularities of the earth upon an experimental coupling curve and to determine the minimum number and length of exploring wires which it is necessary to use in order to be reasonably confident of the accuracy of the results. The data indicate that if only one of the seven groups of 200-ft. exploring wires had been used, the maximum deviation of any one point from the corresponding point on the average curve would have been less than 25 per cent and that the probable deviation would have been less than 10 per cent. This deviation could probably be reduced by using a somewhat longer exploring wire.

Measurements were also made of the voltage induced in sections of the telephone line when the power line was energized with ground-return current. A comparison of the measured values of the mutual impedance and those given from calculations using the coupling curves of Fig. 18 are given in Table III. With the exception of the section from pole 5134 to 5211, for which the calculations may be subject to some error due to proximity to the end of the disturbing circuit, and the section from pole 5614 to 5682, the agreement between measured and calculated values is satisfactory.

D-C. Determination of Earth Conductivity. In con-

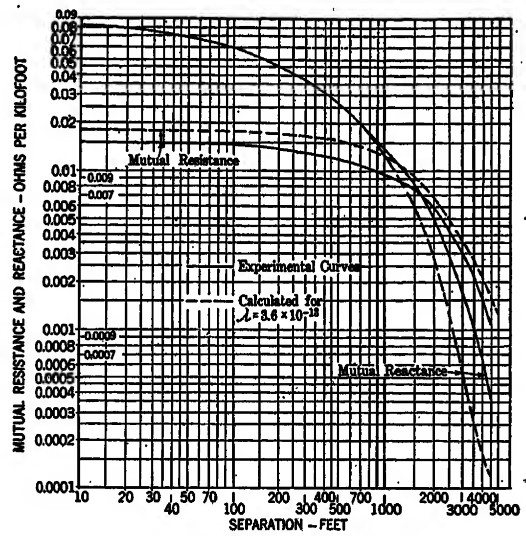

FIG. 18—MASSILLON TESTS

Experimental values of mutual resistance and reactance

sidering the experimental results described above, particularly the reasonably good agreement between the experimental coupling curves and those calculated by means of the Carson formulas with suitably chosen

TABLE III
MASSILLON TESTS

Measured Mutual Impedances of Power and Telephone Circuits and Comparison with Values Calculated from Experimentally Determined Coupling Curves

Exposure		Measured mutual impedance-ohms	Calculated mutual impedance—ohms
From pole	To pole		
5134	5211	0.0308 /45.9°	0.0415 /35.5°
5211	5268	0.0532 /44.7°	0.0442 /34.2°
5268	5386	0.282 /63.7°	0.280 /64°
5386	5511	0.0707 /30.3°	0.0630 /28.2°
5511	5614	0.0386 /29.7°	0.0427 /28.5°
5614	5682	0.0164 /18.4°	0.0117 /14.8°
5682	5805	0.141 /62.4°	0.149 /59.2°
5134	5805	0.609 /53.7°	0.612 /52.5°

earth conductivity, it seemed desirable to investigate whether an experimental value of earth conductivity alone would be sufficient information for the determination of coupling curves with enough accuracy for many

purposes. With this in mind, an investigation has been undertaken of more direct methods for determining the conductivity of the earth or more generally of methods for determining the structure of the earth in a particular location (whether homogeneous or stratified and, if the latter, the thickness of the strata) and the earth conductivity. The work is at present only in an early stage, but a brief statement of the method followed and of the results so far obtained may be of interest.

The procedure followed amounts to an investigation of the mutual resistance of a number of suitably located ground-return circuits, with direct current. It will be recalled that in an earlier part of the paper it was stated that for a homogeneous earth the mutual resistance of two ground-return circuits, for direct current, can be easily derived, and expressed in a formula involving only the earth conductivity and the distances between the grounding electrodes. For a stratified earth, similar formulas have been worked out involving the distances between the grounding electrodes and the conductivities, and the thicknesses of the several strata. By means of measurements of the mutual resistance for direct currents of circuits with suitably located ground electrodes, the conductivities and thicknesses of the strata can then be determined.

Practically, the experimental work presents many problems, among them being the elimination of the effects of stray earth currents and evaluation of the effects of local irregularities in earth conductivity. A preliminary trial of the method was made in connection with the tests at Massillon, and while local irregularities were found to be quite marked, yet the average earth conductivity in the region covered by the tests was about 1.5×10^{-13} abmhos per cm. cube, which is not greatly different from that indicated by the coupling tests. A quite extended series of tests at Cross Keys, using an improved technique, yielded results in excellent agreement with the hypothesis that at this location the earth is stratified, having an upper layer about 150 feet thick with a conductivity about 3.4×10^{-15} and a conductivity in the lower stratum about 2.6×10^{-13}.

Conclusion

In conclusion, it is well to recall the end towards which the work described in this paper has been directed. It was desired, first, to obtain a sufficiently detailed experimental study of the mutual impedances of ground-return circuits to enable the formation of an adequate picture of the physical phenomena involved; also to test out the theoretical formulas available. Second, the aim was to investigate practical means for enabling the calculation of the ground-return mutual impedances of power and telephone lines.

With regard to the first item, it was found that an analysis in terms of an "equivalent ground-plane" was inadequate to represent completely the observed phenomena. However, when information is available as to the proper value of ground-plane depth, this method can be used to advantage in many cases where approximate results only are desired.

A theory based on the assumption of a d-c. distribution in the earth gave a somewhat better explanation, particularly in connection with the mutual impedances of circuits in which the points of ground connection were in close proximity, but left much to be desired in the way of quantitative agreement with the experimental results. The results of a theory which considers the effect of eddy currents in the earth are shown to be in fair qualitative agreement with some of the test values, and by a slight extension of the theory, good quantitative agreement can be found. This theory, however, does not explain end effects.

In the investigation of practical means for enabling the calculation of the mutual impedances of power and telephone lines a scheme involving the experimental determination of a coupling curve has been found to give quite satisfactory results. Further work is to be done on this problem, and similar tests must be made in several other locations before the method can be considered completely satisfactory. Other methods are also being investigated.

Acknowledgment

The authors wish to express their appreciation of the assistance of Messrs. F. J. Grueter and B. C. Griffith in the field testing, analysis of the data and preparation of this paper, also to many others who have aided in this work. Thanks are due to the operating power and telephone companies who lent the facilities for some of the work described, and to members of their organizations who assisted in the tests.

Bibliography

The following list is far from complete, but covers the more important papers which were consulted in the course of the work:

1. California Railroad Commission, Inductive Interference, 1919.

2. "Mutual Impedances of Grounded Circuits," G. A. Campbell, *The Bell System Technical Journal*, October 2, 1923, pp. 1-30.

3. "Ueber die Berechnung der Magnetischen Inducktion und Wechselstromleitungen mit Erdruckleitung," F. Breisig, *Telegraphen und Fernsprechtechnik*, April 14, 1925, pp. 93-98.

4. "Die Erde als Wechselstromleiter," O. Mayr, *E. T. Z.*, 46, September 1925, pp. 1352-1436.

5. "Die Ausbreitung der Erdstrome in der Umgebung von Wechselstromleitungen," R. Rudenberg, *Zeit. fur Angew. Math. und Mech.*, October 5, 1925, pp. 361-389.

6. "Ueber das Feld einer Unendlich Langen Wechselstrom Durch Flossenen Einfachleitung," F. Pollaczek, *Elektrische Nachrichten Technik*, September 3, 1926, pp. 339-359; January 4, 1927, pp. 18-30.

7. "Wave Propagation in Overhead Wires with Ground Return," J. R. Carson, *The Bell System Technical Journal*, October 5, 1926, pp. 539-554.

8. "Theorie der Leitung von Wechselstrom Durch die Erde," G. Haberland, *Zeit. fur Angew. Math. und Mech.*, October 6, 1926, pp. 366-379.

9. "Gegenseitige Induktion Zwischen Wechselstromleitungen von Endliche Lange, F. Pollaczek, *Ann. der Physik*, Vol. 87, Dec. 1928, pp. 965-999. This paper treats of the mutual impedances of circuits of finite length. However, the assumptions regarding conditions at the ground connection seem to depart considerably from the practical conditions of the experiments reported in the present paper. For this reason, and the fact that numerical evaluations by these formulas are very laborious, no calculations by this method have as yet been made for comparison with the experimental results.

Discussion

E. P. Peck: In this paper, the authors have drawn some conclusions regarding the structure and conductivity of the earth at the test location near Cross Keys, N. J. One of the other Project Committees of the Joint Subcommittee on Development and Research had previously made similar tests at this same location, from which the effective conductivity was determined by the same method as that used by the authors of this paper. In addition, because of the wide range of frequency used in

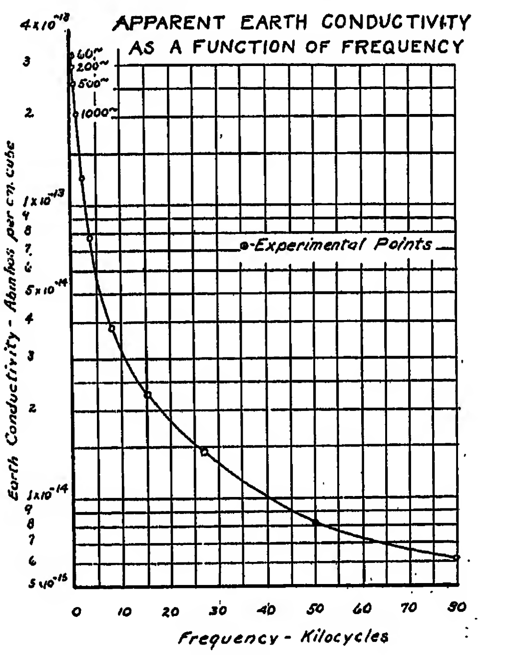

FIG. 1

these tests, it was possible to check an hypothesis as to the structure of the earth by a method entirely different from those described in the paper. The conclusions from the two different methods of attack are quite similar and it may be of interest to consider these other tests.

The tests described here were carried on, in connection with studies of inductive coordination at carrier frequencies. The mutual impedances were determined for the same circuits described in the paper, for a frequency range from 60 to 80,000 cycles. In these measurements, however, no attempt was made to determine the phase angle between the induced voltage and the inducing current.

By substituting the measured values of mutal impedance in Carson's formula, an effective value of earth conductivity was obtained for each frequency. A curve showing the variation of the earth conductivity with frequency is given. It will be seen that at 60 cycles, a value of earth conductivity of 3.3×10^{-13} is indicated and that if the curve is extrapolated a limiting value of earth conductivity at the higher frequencies is approximately 5×10^{-15}.

In the case of a circuit with ground return energized with alternating current, the distribution of the earth current will be such that the impedance of the circuit will be a minimum. When the frequency of the current is low, the resistance of the earth return will be the controlling factor and the current will spread over a large cross section of the earth. At the higher frequencies, the inductance becomes the controlling factor and the earth return current will tend toward concentration in a much smaller cross-sectional area of the earth near the metallic conductor.

If the structure of the earth is such that there is an upper layer of poor conductivity and a lower layer of good conductivity, the apparent conductivity of the earth as determined from measurements of mutual impedance, will decrease with an increase of frequency until all of the current is in the upper layer and the apparent earth conductivity becomes a constant value. Using this method of analysis, the data yields the following conclusions: value of earth conductivity of the lower layer approximately 3.3×10^{-13} abmhos per cm. cube; value of earth conductivity of the upper layer approximately 5×10^{-15} abmhos. These values are in very good agreement with the results described in the paper where the earth conductivity determined directly from d-c. measurements indicated a conductivity of the lower layer of 2.6×10^{-13} and the upper layer of 3.4×10^{-15}.

A comparison of the apparent earth conductivity from the two tests is given in the table below:

APPARENT EARTH CONDUCTIVITY

Frequency	Table I of paper	Tests described in this discussion
60	4.2×10^{-13}	3.3×10^{-13}
200	3.75×10^{-13}	2.95×10^{-13}
500	2.76×10^{-13}	2.6×10^{-13}
1000	2.0×10^{-13}	2.0×10^{-13}

E. B. King: From the standpoint of the practical operating problem, it may be of interest to point out the extent to which mutual impedance tests between power and communication circuits have been conducted in the past year, together with a brief discussion of some of the methods used in making these tests.

Incomplete records show that over thirty sets of cooperative tests have been made in various parts of Canada and the United States during the past twelve months.

These tests indicate a wide range of equivalent earth conductivities from about 2×10^{-12} to approximately 10^{-15} c. g. s. electromagnetic units. A summary of the results indicates that there were four cases with earth conductivities between 10^{-11} and 10^{-12}, fourteen cases between 10^{-12} and 10^{-13}, ten cases between 10^{-13} and 10^{-14} and four cases between 10^{-14} and 10^{-15}. In several of these exposures the separation was one-half mile or more. At a separation of 3000 ft. the ratio of the mutual impedance between the power and communication circuits would be approximately 20 to 1 for a range of earth conductivity between 10^{-12} and 10^{-13}, in which limits about 75 per cent. of the exposures fell. For these same limits at a separation of 1000 ft. the ratio would be about 5 to 1, while for roadway separations, the ratio is less than 2 to 1. This wide range of earth conductivities and the resulting effect on the mutual impedance indicate the necessity for making mutual impedance tests, especially in cases of wider separations, where it is desired to obtain a reasonably accurate picture of the probable voltages that may be induced on the communication circuits. The cooperative tests that have been made fall under the following two general classifications:

1. Tests with the power line energized at low single phase voltage and grounded beyond the limits of each end of the exposure.

2. Tests with the power line energized at normal operating voltages, and the voltage induced on the communication circuits measured by means of automatic recording oscillographs at times of faults placed between one or more phase conductors and ground.

Most of the tests made come under the first classification.

In the tests described in the paper by Messrs. Bowen and Gilkeson an alternating current potentiometer was used to determine the magnitude and phase relation of the mutual impedance. However, such an instrument is not ordinarily available to operating companies wishing to conduct cooperative tests. Where the induced voltages are about 15 volts or more, standard a-c. voltmeters, ammeters and wattmeters can ordinarily be used with sufficient accuracy. For lower induced voltages down to about one-half volt, satisfactory results can usually be obtained by means of thermocouple voltmeters, amplifier voltmeters, and low power factor wattmeters.

D. A. Pierce: The tests described by Messrs. Bowen and Gilkeson are very necessary and apparently give satisfactory results. However, with tests of this character as with tests of most any other nature, a large part of the story in obtaining the final result is in an interpretation of the test results. Messrs. Bowen and Gilkeson have presented a most satisfactory discussion of ways and means for obtaining certain test results but they have not considered it within the scope of their paper to attempt an interpretation of the results obtained.

The work which they have conducted is primarily in connection with the study by the Joint Subcommittee on Development and Research of the coordination of power and communication lines. The power companies have made considerable progress in recent years in improving the operating characteristics of their lines. However, we have not as yet progressed to a point where there are not occasional breakdowns of insulators between conductor and earth. This breakdown of insulation results in a flow of current out over the conductors, with a return through the earth. This current in turn will produce a voltage in any nearby communication circuits, with its magnitude depending upon the magnitude of the coupling factor between the circuits and the current in the earth. By the use of the method of "Symmetrical Components," which has been developed by C. L. Fortescue and others, the fault current can be calculated and the ground current determined for any given condition with a reasonable degree of accuracy. This paper points out means for obtaining the coupling between the two circuits. These two factors permit us to calculate the induced voltage in the telephone line for an assumed given condition. Unfortunately, this does not complete the story in a coordination problem. We must also take into account the probability of the assumed condition of current—the number of times that the given condition will occur in a given length of time. In other words, a situation which would induce a given voltage "a" in a telephone line once in five years is entirely different from a situation which would induce the same voltage "a" into the telephone line once a week or even once a month.

Other factors, such as the effect of a given voltage in a telephone circuit, the distribution of this voltage between various parts of the circuit, and means for mitigating the voltage must also be considered before a complete answer can be given.

The Joint Subcommittee on Development and Research is working on all of these factors and hopes that within a reasonable time satisfactory answers can be obtained. However, much remains to be done before complete answers to all of these questions are known to the American industry and in the meantime we are simply going on trying to determine a reasonable solution based upon the facts we have in each case.

L. P. Ferris: Geological conditions undoubtedly influence the "equivalent earth conductivity" in different locations which we obtain when we compare experimental results with theoretical computations based upon the usual assumption of a homogeneous earth. It will be interesting as studies of this nature progress to endeavor to correlate the results with geological conditions.

I should like to bring to your attention a point which should be of interest to those applying the methods proposed in the paper to the practical predetermination of induced voltage. In mountainous districts it is not uncommon to find the strata of the earth greatly inclined with respect to their original horizontal position. This is evidenced by the outcroppings of the rock at the surface, some of these outcroppings showing the strata to be almost perpendicular. In such a region I believe the direction of the primary circuit with respect to the direction of the stratification planes has an important influence on the resulting distribution of the current in the earth, and hence, upon the mutual impedance between grounded circuits. It seems evident that if the primary circuit is parallel to the stratification planes, the distribution of earth current in the different strata, once we are beyond the region of end effects, will tend to remain constant from one location to another without the necessity of the current passing from one stratum to another. Under this condition, also, the current would tend to concentrate in the strata of higher conductivity. In contrast to this condition, if the primary circuit runs at right angles to the stratification planes, the earth current throughout the length of the line will have to pass from one stratum to another, giving a different distribution of earth current than in the first case. Under these conditions, we should certainly expect the coupling to be different, and, I believe, generally greater than in the case where the circuits all run parallel to the strata.

In the study of a specific case, which led to these conclusions, six short secondary lines were laid out parallel to a railway circuit in a region where the railway circuit was closely parallel to the planes of upturned strata, for about ten miles. In this same locality, a telephone line paralleled the railway circuit. By measurements in the railway circuit and in the short secondary circuits, a curve showing the relation of mutual impedance to separation between circuits was determined. From this curve and an accurate survey of the railway and telephone lines, the over-all mutual impedance in the ten-mile section was estimated and compared with the actual mutual impedance determined by measurements. The agreement in this case was good, the estimated value being about 4 per cent. high. Based on this same coupling curve, estimates were also made of the mutual impedance in two other sections of exposure 3½ and 8 miles in length, in the same vicinity as the section just mentioned, but generally at right angles thereto, which gave a condition where the primary current must pass from stratum to stratum. The over-all coupling for each of these sections was measured and compared with the estimated values. For the 3½-mile section, the estimated value proved 46 per cent too low and for the 8-mile section 21 per cent lower than the measured value.

I would conclude, therefore, that in regions of considerable stratification of the earth which is much inclined to the horizontal, the results of coupling tests where the current paths are in one direction with respect to the prevailing planes of the strata, should not be expected to apply accurately to an exposure, even in that immediate vicinity, in which the path of the inducing current would necessarily be at a markedly different angle with respect to the stratification planes. This, of course, is of more importance at larger separations where a difference in effective earth conductivity has more effect upon the coefficient of induction than at small separations. I hope that it may be possible in the future for an experimental investigation to be made, in which the system of primary and secondary circuits employed to determine a coupling curve, may be rotated from a position parallel to the outcroppings of strata to one at right angles thereto. I believe the results to be obtained will be both interesting and important.

L. C. Peterson: The paper deals with a subject which is of great interest to both power and telephone engineers. The phenomena discussed, however, apply only to steady state conditions. Under certain circumstances the transient induced voltages may also be of importance. It may, therefore, perhaps be of interest to mention some work which has been done on this problem. In a forthcoming issue of the *Bell System Technical Journal* this work will be discussed more fully.

Consider a system of two wires, 1 and 2 (wire 1 being infinite in length and hence end effects are neglected), parallel with each other and located on the surface of the earth but insulated from it except at the ends. The distance between the wires is x cm. Let the voltage on wire 2 due to a unit current step (that is, a current equal to zero before $t = 0$ and unity thereafter) on wire 1 be denoted by $Z_{12}(t)$; then, the voltage on wire 2 due to a current $I(t)$ in wire 1 is given by the following formula:

$$V_{12}(t) = \frac{d}{dt}\int_0^t Z_{12}(\tau)\, I(t-\tau)\, d\tau \qquad (1)$$

We shall apply this formula to the calculation of the transient induced voltage due to the sudden flow of a current $I(t) = \sin\omega t$. As $I(0) = 0$, formula (1) reduces to

$$V_{12}(t) = \int_0^t Z_{12}(\tau)\, \frac{d}{dt} I(t-\tau)\, d\tau \qquad (2)$$

The fundamental information required is thus a knowledge of $Z_{12}(t)$. In the case under consideration where both wires are located on the surface of the earth it can be shown that $Z_{12}(t)$ is given by

$$Z_{12}(t) = \frac{1}{\pi\lambda x^2}\left(1 - e^{-\frac{\pi\lambda x^2}{t}}\right) \qquad (3)$$

where λ is the ground conductivity. It may be noted that in obtaining this formula use has been made of Carson's fundamental formulas which may be found in reference (4) of the paper by Messrs. Gilkeson and Bowen. From (2) and (3) and by assuming $I(t) = \sin\omega t$ we get

$$V_{12}(t) = \frac{\sin\omega t}{\pi\lambda x^2} - \frac{\omega}{2\pi\lambda x^2}\left[e^{j\omega t}\int_0^t e^{-\frac{\pi\lambda x^2}{t} - j\omega t}\, d\tau + e^{-j\omega t}\int_0^t e^{-\frac{\pi\lambda x^2}{t} + j\omega t}\, d\tau\right] \qquad (4)$$

The solutions of the integrals appearing in (4) are not known in closed form. The following series expansions for small and large values of time may be derived however:

$$V_{12}(t) = \frac{\sin\omega t}{\pi\lambda x^2} - \frac{\omega}{\pi\lambda x^2}\, e^{-\frac{\pi\lambda x^2}{t}}\left(t^2\,\frac{\cos\omega t}{\pi\lambda x^2} + t^3\left(\frac{\omega\sin\omega t}{\pi\lambda x^2} - \frac{2!\cos\omega t}{(\pi\lambda x^2)^2}\right) + t^4\left(\frac{3!\cos\omega t}{(\pi\lambda x^2)^3} - \frac{3\,\omega\sin\omega t}{(\pi\lambda x^2)^2} - \frac{\omega^2\cos\omega t}{\pi\lambda x^2}\right) + \dots\right) \qquad (5)$$

and

$$V_{12}(t) = -\frac{1}{\omega}\left(\frac{1}{t^2} - \frac{\pi\lambda x}{t^2} + \frac{1}{t^4}\left(\frac{(\pi\lambda x^2)^2}{2!} - \frac{3!}{\omega^2}\right) + \dots\right) + S \qquad (6)$$

where S denotes the steady state voltage.

For such values of time where neither of these series expansions would give very accurate results some means of mechanical integration has to be employed.

The complete expression for the disturbing current contains in addition to the term $\sin\omega t$ also the term $\epsilon^{-\beta t}$ where β is the damping constant of the circuit. For small values of time the voltage due to the current $\epsilon^{-\beta t}$ may be found by a process analogous to that used in obtaining equation (5), while for larger values of time mechanical integration must be resorted to.

For more complicated time functions of the disturbing current, the analytical evaluation of the integrals becomes quite difficult and mechanical integration must be used.

K. L. Maurer: A very interesting feature of this paper is the description of methods of obtaining experimental information upon which can be based estimates of mutual impedances of ground return circuits in advance of their construction. It is usually a relatively simple matter to measure the self and mutual constants of circuits which either directly or indirectly involve the earth, after the circuits have been established. However, it often is important to have information on such constants in advance of construction as they may have a material bearing on features of design. The importance of this in relation to the problem of inductive coordination of power and communication systems is obvious.

A knowledge of the self and mutual constants, on a ground return basis, of elements of electrical networks is also often of importance in connection with other problems in the fields of communication and power transmission. For example, in the case of a fault on a transmission line, from line to ground, the self-impedance of the faulted phase and the division of return current between ground wire and earth involve grounded circuit theory. Another good example is the propulsion systems of electrified railroads using the running rails to return all or a part of the current. Determination of self and mutual impedances of various elements of the propulsion network and the amount of current escaping from track to earth require a knowledge of the ground return constants of these circuit elements.

A series of field tests was completed several months ago in the eastern part of Pennsylvania in connection with advance estimates of induced voltages from a railroad electrification. The testing arrangements were generally similar to those used at Cross Keys, as described in the paper. The primary circuit consisted of a straight wire laid on the ground and connected to

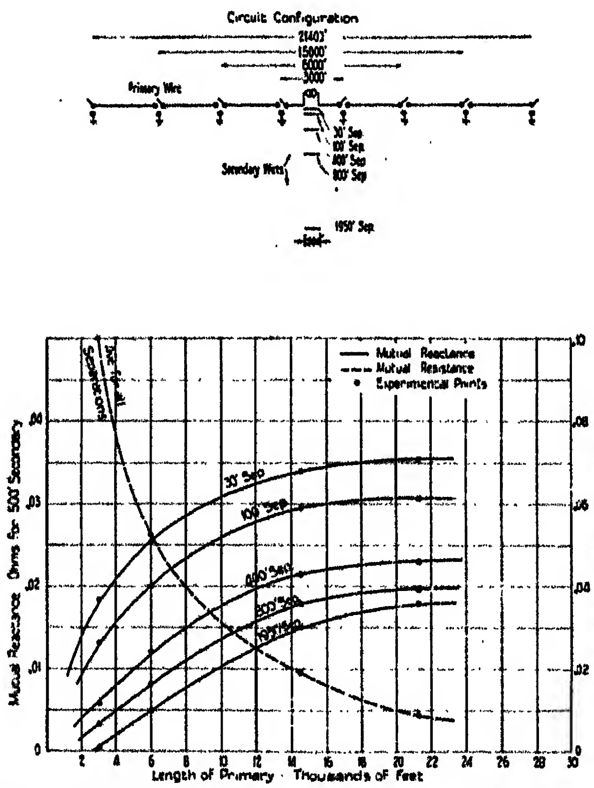

FIG. 2—VARIATION OF MUTUAL IMPEDANCE BETWEEN SHORT PARALLEL STRAIGHT WIRES GROUNDED AT THEIR ENDS AS THE LENGTH OF ONE WIRE IS VARIED

ground rods at its terminals. This wire was unreeled from a specially equipped motor truck which also contained a variable frequency generator used for energizing the primary. For the secondary, or disturbed circuits, wires were also laid on the ground parallel to the primary at various separations from it and grounded at the terminals. The secondaries were unreeled from a second truck which was equipped with apparatus for determining the mutual impedance. Testing frequencies between 25 and 75 cycles were used.

One object of the tests was to cover a large number of locations in as short a time as possible, and the equipment was designed and the test procedure arranged to promote this end. For practical reasons it was desired to limit the primary length to 5000 or 6000 ft. The secondaries were arranged symmetrically about the center of the primary and their length was generally limited to 500 ft. to avoid effects due to proximity of the primary and secondary ground connections. Separations from 30 to 2000 ft. were used.

It was discovered in the early stages of the tests that for this circuit arrangement, the real component of the observed mutual impedance was much larger than could reasonably be accounted for by the infinite length circuit theory of Carson[1] and Pollaczek.[2] From this it was suspected that the spacing of the primary and secondary electrodes was not sufficiently wide to avoid end effects. A value of ground conductivity was obtained from the real component by the use of the Campbell[3] expression for mutual resistance which is predicated upon a d-c. distribution of earth current. When this value of conductivity was substituted into the Carson equation for the mutual reactance, a much larger value was obtained than had been measured. This observation led to the conclusion that for this locality, the primary length of 6000 ft. was too short to approximate the conditions upon which the Carson theory is based.

A test was made to investigate the behavior of the mutual impedance for a given frequency between two parallel grounded wires, arranged symmetrically, as the length of one of the wires was increased from about 3000 ft. to about 21,000 ft., the length of the other remaining fixed at 500 ft. The results of this test, shown on the accompanying curves are interesting. The reactive component of the mutual impedance is seen to increase quite rapidly with primary length between 3000 and about 10,000 ft., beyond which the increase is more gradual. The real component of the mutual impedance, on the other hand, is seen to decrease quite rapidly with increasing primary length up to about 15,000 ft. The trend of these curves indicates that both components would become about constant at primary lengths of 25,000 to 30,000 ft.

The results of these tests with a plurality of primary lengths were useful in interpreting the results of the tests in which the 6000-ft. primary was used.

J. Riordan: The experimental observations given in this paper by Messrs. Bowen and Gilkeson are for a steady state condition with periodic current. It may be of interest to describe briefly some work done in finding formulas for the transient impedances of ground return circuits, which is based upon a formula for steady state mutual impedance between ground return wires of finite length recently given by R. M. Foster.[4] Mr. Foster's formula for the mutual impedance between differential elements of two wires is in a remarkably simple form. While the integrations necessary to obtain a formula for straight wires of finite length cannot be effected in closed form in terms of known functions, the integrations can be performed for a unit step current. My result is as follows:

The voltage in wire 2 of two straight parallel wires separated by distance x, lying on the surface of the ground and insulated from it except at the ends, with unit step current (zero $t < 0$, unity $0 < t$) in wire 1, is given by the following formula:

$$Z_{12}(t) = \frac{1}{2\pi\lambda}\left[\phi(z_2+a)-\phi(z_1+a)-\phi(z_2-a)+\phi(z_1-a)\right] \tag{1}$$

Here the rectangular coordinates of the terminals of wire 1 are $(o, o, -a)$ and $(o, o, +a)$ and of wire 2 are (x, o, z_1) and (x, o, z_2); λ is the ground conductivity in electromagnetic c. g. s. units. The function appearing is:

$$\phi(u) = \frac{-1}{\sqrt{x^2+u^2}} + \frac{\sqrt{x^2+u^2}}{x^2}\,\mathrm{erf}\left(\sqrt{\frac{\pi\lambda}{t}}\,\sqrt{x^2+u^2}\right) - \frac{u}{x^2}\exp\left(-\frac{\pi\lambda x^2}{t}\right)\mathrm{erf}\left(u\frac{\sqrt{\pi\lambda}}{t}\right)$$

$$\text{where } \mathrm{erf}(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-u^2}\,du$$

The time is in seconds and distances are in centimeters; the dimensions of the result are abvolts per unit abampere, that is, abohms.

When wire 1 is made infinite this formula reduces to the corresponding formula (per unit length of wire 2) given in L. C. Peterson's discussion of this paper, namely:

$$\frac{Z_{12}(t)}{z_2-z_1} = \frac{1}{\pi\lambda x^2}\left[1-\exp\left(\frac{-\pi\lambda x^2}{t}\right)\right] \tag{1a}$$

When the current in wire 1 is a function of the time such as is ordinarily found, $1 - e^{-\gamma t}$, $e^{-\gamma t}\sin w t$, $\sin w t$, or combinations thereof, the resulting voltage is not expressed in terms of known functions. My results for these cases are not given here because the formulas are complicated. In practical computation when curves of $\phi(u)$ given above are available, it is probably more expedient for these time functions of current to use Carson's extension formula, one form of which is:

$$V(t) = \frac{d}{dt}\int_0^t I(t-T)\,Z_{12}(T)\,dT$$ [5]

and perform the integration numerically or mechanically.

A. E. Bowen and C. L. Gilkeson: The excellent agreement between the results reported in the paper and those reported by Mr. Peck is very gratifying, and lends further support to the theory advanced in the paper as to the stratified nature of the earth at the Cross Keys location.

The discussions by Messrs. King and Pierce are a valuable addition to the paper for they show the relationship of this work to the general problem of inductive coordination.

The discussions by Messrs. Ferris and Maurer have brought out the importance of several precautions which should be taken in using the exploring wire method of predetermining the mutual impedance of power and telephone circuits. One of these possible sources of errors, as brought out by Mr. Ferris, is the possibility of the earth conductivity changing appreciably within the length of the line. Because of this possibility, where the exposure is long, or where there is some indication that the earth structure may change within the exposure, exploring wire measurements should be made at two or more points within the exposure. If such a precaution is not followed the results of the tests may apply to only one section of the exposure and may result in a very misleading idea of the total coupling between the two circuits.

1. Reference 7 of paper by Messrs. Bowen and Gilkeson.
2. Reference 6 of paper by Messrs. Bowen and Gilkeson.
3. Reference 2 of paper by Messrs. Bowen and Gilkeson.
4. Bulletin of the American Mathematical Society, May, 1930, pp. 367-368 (Abstract).

5. *Electric Circuit Theory and the Operational Calculus*, J. R. Carson, McGraw-Hill Co., 1926, p. 16.

Another possible source of error may be due to local irregularities where the exploring wires are installed. A limited amount of experience has indicated that if a coupling curve (such as that shown in Fig. 16) is determined from measurements in exploring wires at several separations using an exploring wire length of at least 500 ft. these errors are partially averaged out and the remaining error should be quite small.

The discussion by Mr. Maurer on the effects caused by proximity of the ground on the disturbing and disturbed circuits is of great interest, and the experimental results given in his curves are a valuable contribution. The method of attack is different from that chosen by the authors, but the results seem at least qualitatively in accord with those given in the paper. The experimental investigation of the problem seems not yet far enough advanced so that the relative importance of the factors influencing this effect can be evaluated. It seems evident, however, that the region in which end effects will be felt will vary widely in different locations, being greatly influenced by the ground conductivity. The structure of the earth and the frequency of the current will also affect the extent of this region.

The calculated curves of Fig. 10 in the paper illustrate roughly the effect of earth conductivity upon the extent of this area. The effect of the frequency of the current in the disturbing circuit should be such that as it is increased the region influenced by "end effect" is somewhat reduced. Further tests are in progress to amplify our information on these points.

In the area influenced by end effects three phenomena are present which do not appear in other parts of the exposure. Two of these are illustrated in Fig. 5 of the paper, which shows that within this region the gradient of mutual impedance parallel to the disturbing circuit is not a constant and that the gradient perpendicular to the circuit is far from being negligibly small. Fig. 6 shows that near the point of grounding the phase angle of mutual impedance is very small, gradually increasing to a constant value at the point where end effect fades out. Since the region affected depends so largely upon earth conductivity, no rule can be given as to the minimum length of the disturbing circuit which may be used with exploring wires. For this reason steps should be taken in any particular case to assure that the primary line is made so long that the voltages induced in the exploring wires are free from end effects.

Since the paper was written a more complete study of the end effect phenomena has been made at Cross Keys. This includes the determination of the magnitude and direction of the gradient of mutual impedance within a radius of 2000 ft. of one of the electrodes. These measurements have added much to our knowledge of the phenomena but have not changed any of the results given in the paper.

The discussions of Messrs. Peterson and Riordan concerning voltages induced by transient currents are of considerable interest. There is but a small amount of experimental information available on this phase of the problem and much work remains to be done. It is noted that in both developments theoretical formulas for the steady-state mutual impedances are used, and in this respect, the work given in this paper should be useful.

Effects of the Magnetic Field
on Lichtenberg Figures

BY C. EDWARD MAGNUSSON[1]

Fellow, A. I. E. E.

Synopsis.—This paper deals with new forms of Lichtenberg figures produced under the combined stress of dielectric and magnetic fields. The effects produced by the magnetic field may be used for determining whether electrons, positive ions, or protons, are basically the active elements in the formation of the positive as well as the negative figures. The photographs also show that the presence of the magnetic field greatly extends the range of air pressures within which figures of definite form can be obtained; that figures taken at low air pressures possess structures strikingly different from those hitherto known; and that these figures may prove a key to the mechanism of the electric spark.

* * * * *

MANY extensive investigations have been made to ascertain the nature of Lichtenberg figures and lately, on their use for recording certain characteristics of electric surges and impulses, for measuring short time intervals, etc.; but no attempt seems to have been made to determine what effects, if any, would be produced on the figures if formed under the stress of the magnetic field. That a reaction should be expected is

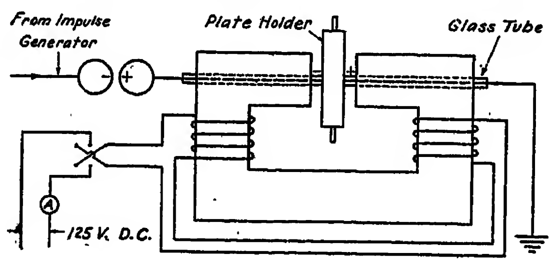

FIG. 1—CIRCUIT DIAGRAM

Photographic plates: Lumiere, Sigma, 3¼ in. x 4¼ in. (8.3 x 11.8 cm.)
Source of voltage: "Static" from a belt.
Spark-Gap: Copper spheres, 10 in. (25.4 cm.) in diam.
Electromagnet: movable cylindrical pole cores, 2.8 in. (7.1 cm.) in diam. Circular pole faces, 2.8 in. (7.1 cm.) in diam., in parallel planes; spacing of pole faces, (space occupied by plate holder) for the figures reproduced in this paper: 1.18 in. (3 cm.)

evident, if the figures are formed by rapidly moving electrons, ions or protons, as has been postulated in the several theories advanced to explain the phenomena.

The experimental results are in fact striking and provide the means for determining whether electrons, ions, or protons, are basically the active elements in the formation of the positive as well as the negative figures. The photographs show also that the presence of the magnetic field greatly extends the range of air pressures within which figures of definite form can be obtained; that at low air pressures the structures of the figures are radically different from those hitherto known; and that these figures may prove a key to the mechanism of the electric spark.

This paper deals with the results obtained during the first stage of an investigation on the effects produced by the magnetic field on Lichtenberg figures in progress at the University of Washington. The 280 photographs already taken form a very interesting exhibit; but unfortunately many features of the photographic records cannot be satisfactorily reproduced in halftone cuts.

A diagram of the electric circuit and the arrangement of the apparatus used in the experiments is shown in Fig. 1. The following data will serve in place of a detailed description of the equipment:[2]

A cross-section of the plate holder loaded with two plates, as used in the first part of the work, is shown in Fig. 2.

A pair of photographic plates were placed with the emulsion side outwards; that is in contact with the + and – electrodes. A thin brass plate, 3¼ in. by 4¼ in., was placed between the two photographic plates. For air pressure greater than 25 cm. Hg., the brass plate was not used, as better results were obtained

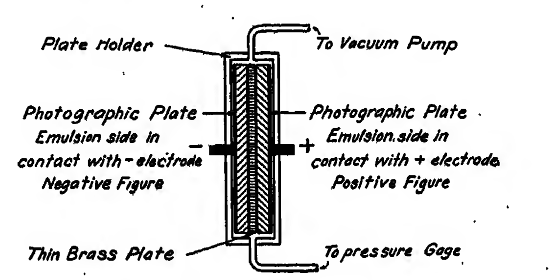

FIG. 2—CROSS-SECTION OF LOADED PLATE HOLDER

without it; but in order to obtain well-defined figures at lower air pressures, it was found necessary to have the brass plate in contact with the two photographic plates, as shown in Fig. 2. By trial, it was found that the positive and negative figures could be taken simultaneously and just as good photographs obtained as when a separate exposure was made for either the positive or the negative figure. By using two plates as shown in Fig. 2, the number of exposures was cut in two, and, what is of greater importance, both the positive and the

1. Professor of Electrical Engineering and Director Engineering Experiment Station, University of Washington.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

2. Lichtenberg Figures, A. I. E. E. JL., Vol. XLVII, 1928, p. 830.

negative figure were obtained for the identical spark or impulse.

For all the figures illustrating this paper, the direction of the magnetic lines of force was perpendicular to the plane of the photographic plate; the direction of the field could be reversed by means of a double-throw field switch. On the legend below each figure, the direction of the magnetic field with respect to the printed page is indicated by the letters N or S. The letter S indicates that the south pole was in front, and

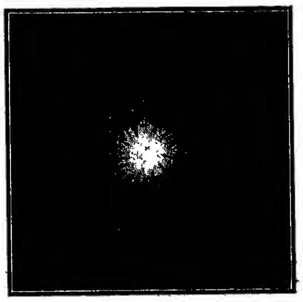

FIG. 3

Pressure 76.1 cm.; Gap 4.0 cm.; Field N, 12,300 cm^2.
Electrode +; Paired with Fig. 4; Neg. No. 193.

the north pole back, of the printed page; that is, the direction of the magnetic lines of force is towards the reader. The notation N indicates the reverse,—the north pole is in front and the south pole back of the printed page, or the direction of the magnetic lines of force is away from the reader.

Under each figure, the legend gives the quantitative

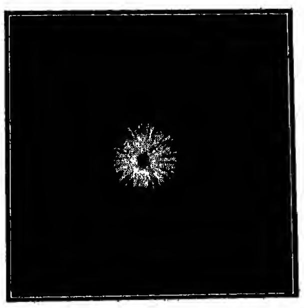

FIG. 4

Pressure 76.1 cm.; Gap 4.0 cm.; Field S, 12,300 cm^2.
Electrode −; Paired with Fig. 3.; Neg. No. 194.

data for the conditions under which the exposure was made. The air pressure is given in cm. Hg.; the spark-gap spacing in cm.; the direction of the magnetic field, N or S; the field strength in lines of force per cm.^{2}; the polarity of the electrode in contact with the emulsion side of the plate as + or − ; and, finally, the number of the corresponding figure in the pair, produced by the same impulse.

Figs. 3 and 4 were taken under normal atmospheric pressure conditions. On careful scrutiny, a distinct bending of the rays or streamers in the negative figure may be noted, but little if any effect can be observed on the positive figure. However, exposures made under less than atmospheric pressure, as illustrated by Figs. 5 to 10 inclusive, show very marked bending and changes in structure of the otherwise radial streamers.

The Negative Figure. For the range of air pressures and impressed voltages represented in Figs. 3 to 10, inclusive, the main effect produced by the magnetic field on the negative figures is the bending of the rays; *clockwise*, if the magnetic lines of force are in the N

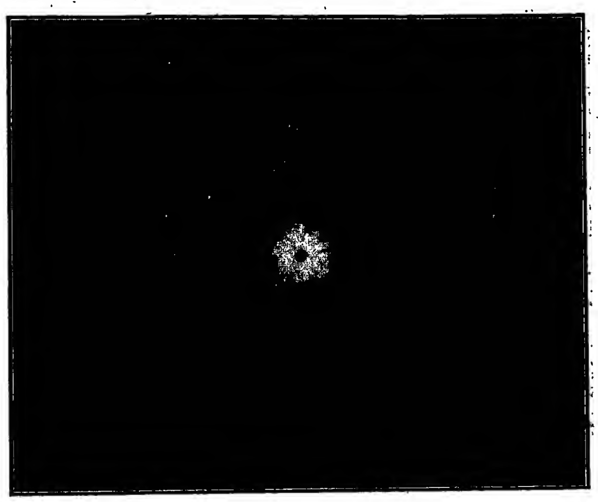

FIG. 5

Pressure 30.0 cm.; Gap 4.0 cm.; Field N, 13,000 cm^2.
Electrode +; Paired with Fig. 6.; Neg. No. 135.

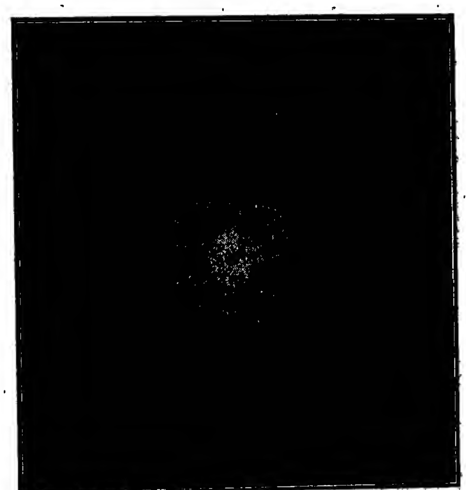

FIG. 6

Pressure 30.0 cm.; Gap 4.0 cm.; Field S, 13,000 cm^2.
Electrode −; Paired with Fig. 5; Neg. No. 136.

direction, as in Fig. 10, and *counterclockwise*, if the field is in the S direction, as in Figs. 6 and 8.

The observed reaction on the negative figure is in full accord with theory. There seems to be little or no difference of opinion as to the mechanism of the formation of the negative figure. The theories are based on the postulate that, under the impulse voltage-gradient, streams or rays or waves of electrons are projected radially from the negative electrode at high velocity

over the emulsion surface of the photographic plate. The effect of the magnetic field in bending the otherwise radially projected rays or streamers is in accord with this assumption. Thus in Fig. 10 the direction of the magnetic lines of force is N; that is, from the reader through the printed page. A stream of electrons projected radially from the negative electrode over the

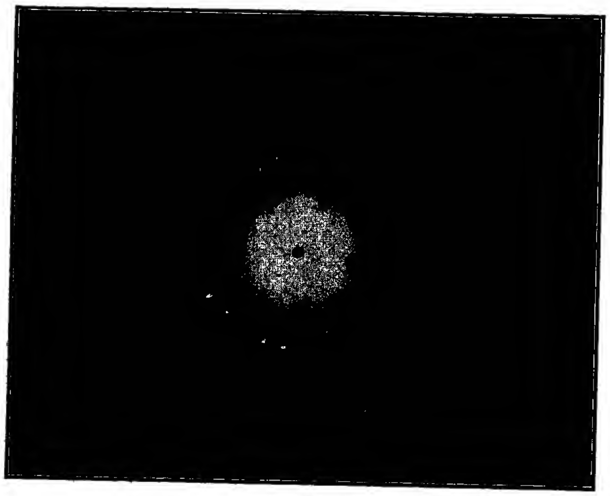

FIG. 7

Pressure 15.0 cm.; Gap 2.5 cm.; Field N, 12,300 cm^2. Electrode +; Paired with Fig. 8; Neg. No. 171.

photographic plate, and therefore at right angles to the magnetic field, should be deflected in a clockwise direction; precisely as shown in the figure. In Figs. 6 and 8 the magnetic field is in the S direction, the reverse of

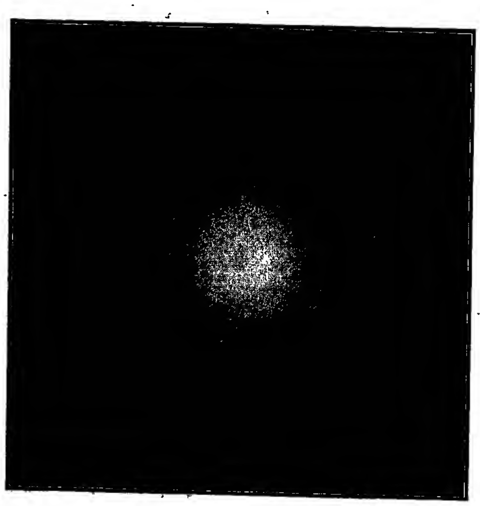

FIG. 8

Pressure 15.0 cm.; Gap 2.5 cm.; Field S, 12,300 cm^2. Electrode −; Paired with Fig. 7; Neg. No. 172.

that in Fig. 10; therefore, the radially projected electrons should be deflected in the counterclockwise direction, which the figures show to be the case. The effects of the magnetic field confirm the assumption that electrons, projected at a high velocity from the negative electrode, are the active elements in the formation of the negative figure.

The Positive Figure. For the positive figure the situation is somewhat more complex, and several theories have been advanced to explain its formation.

Pzribram[3] contends that positive ions, projected radially from the positive electrode are essential fac-

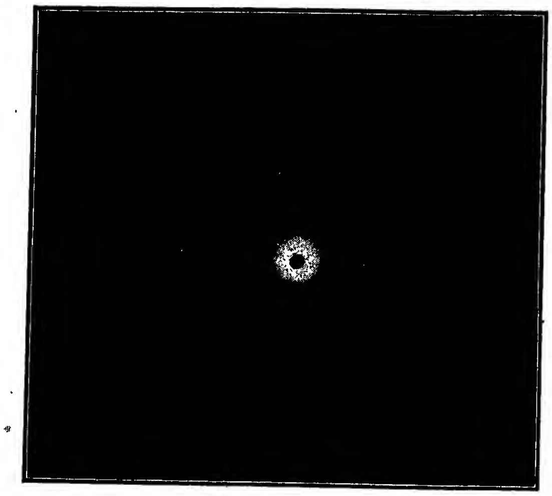

FIG. 9

Pressure 12.0 cm.; Gap 1.2 cm.; Field S, 12,400 cm^2. Electrode +; Paired with Fig. 10; Neg. No. 185.

tors in the mechanism forming the positive figures. He expresses the basic postulates of the theory of formation for both positive and negative figures in the "Fundamentalgegensatz: negatives Elektron—positives Ion."

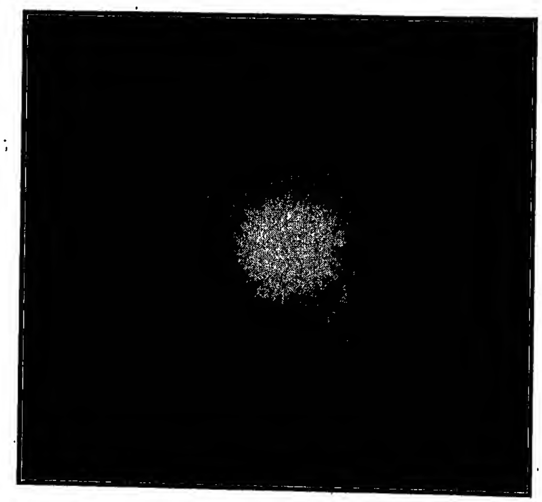

FIG. 10

Pressure 12.0 cm.; Gap 1.2 cm.; Field N, 12,400 cm^2. Electrode −; Paired with Fig. 9; Neg. No. 186.

In order to reconcile the theory with experimental facts, Pedersen postulates protons, positive hydrogen nuclei, as the active elements in place of the more general positive ion. In an important monograph on "The Positive Figure" Pedersen[4] gives a comprehensive

3. K. Pzribram, *Handbuch der Physik*, Vol. XIV, 1927, p. 404.
4. P. O. Pedersen, Lichtenberg Figures III, 1929, p. 105, *Kgl. Danske Vid. Selskab, Math.-Fys. Meddelelser*, VIII, 10.

review of the subject and concludes as follows: "that formation of positive spreaders is due to protons which the strong field at the tip of the spreaders drive outwards with great velocity, by which means electrons are set free in sufficient number to initiate a sudden and strong ionization by collision which again sets free electrons in sufficient numbers necessary to carry away the charge towards the electrode is found to explain throughout in a satisfactory manner the many peculiar features presented by the positive spreaders."

Yoshida[5] offers an entirely different solution: He

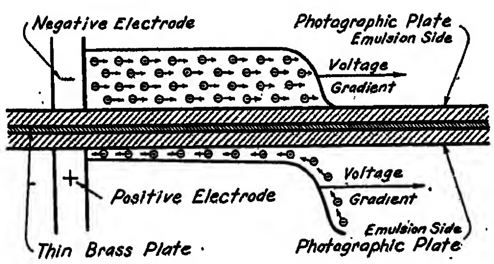

FIG. 11—VOLTAGE GRADIENTS AND ELECTRON STREAMS AT POSITIVE AND NEGATIVE ELECTRODES

holds that the mechanism for the formation of the positive figure consists of electrons attracted by and moving towards the positive electrode. That is, the electrons in motion are the active elements in the formation of both the positive and the negative figures;

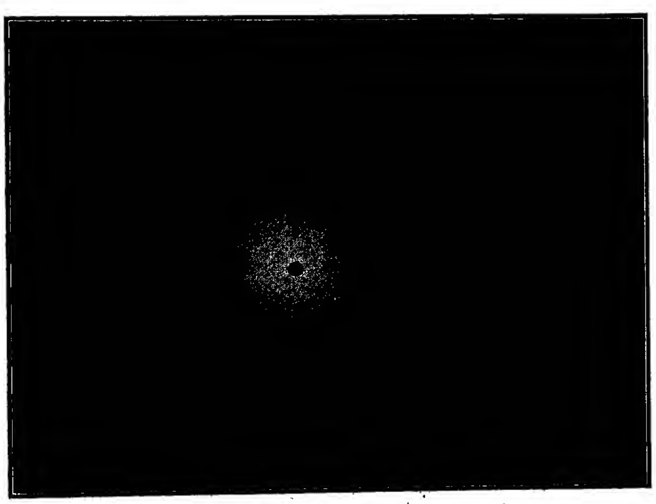

FIG. 12

Pressure 5.0 cm.; Gap 0.6 cm.; Field N, 12,000 cm^2.
Electrode +; Paired with Fig. 13; Neg. No. 213.

motion in direction towards the positive electrode for the positive figure, and away from the negative electrode for the negative figure.

The experimental evidence hitherto available has been inadequate to either fully establish or refute the proposed theories, but it appears that the reaction of the magnetic field will provide the required criterion.

5. U. Yoshida, *Mem. Col. Sci.*, Kyoto Univ., Vol. 2, 1917, p. 105.

In this connection, let the discussion of Figs. 7 and 9 be confined to the space within a radial range of about one inch (2.5 cm.) from the electrode; that is, the reverse bend of the tips of the streamers may be due to other factors which have not as yet been fully determined.

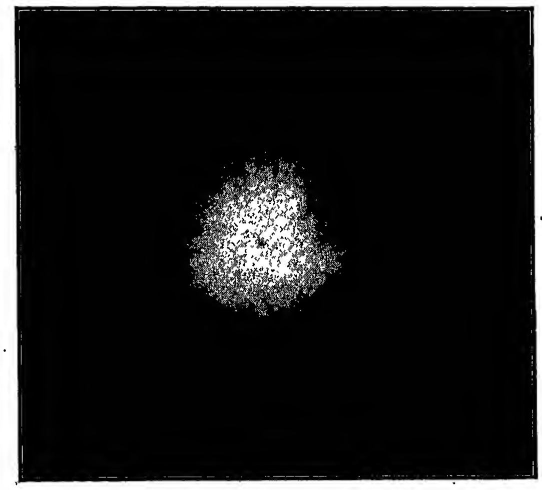

FIG. 13

Pressure 5.0 cm.; Gap 0.6 cm.; Field S, 12,000 cm^2.
Electrode −; Paired with Fig. 12; Neg. No. 214.

Let the argument be applied first to the postulates of positive ions or of protons projected outwards from the positive electrode. Consider the direction of motion that positive ions or protons would have at some point,—as a in Fig. 7,—under the combined stress of the voltage gradient and the magnetic field. The

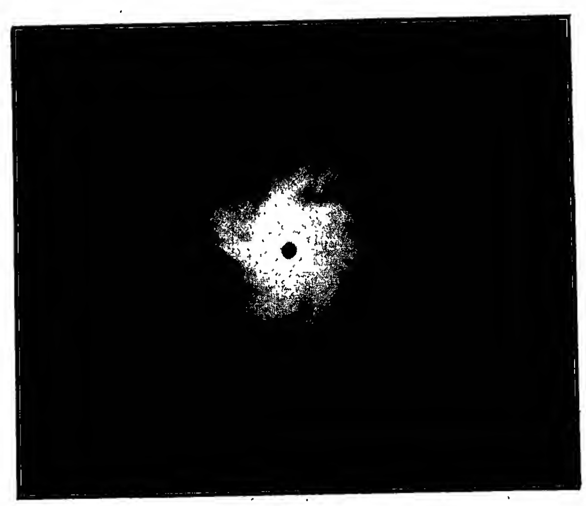

FIG. 14

Pressure 2.0 cm.; Gap 0.5 cm.; Field N, 12,300 cm^2.
Electrode +; Paired with Fig. 15; Neg. No. 326.

magnetic field is in the N direction. The force of the voltage gradient projects the positive charge radially away from the electrode and simultaneously, the reaction of the magnetic field produces a force on the positive ions or protons at right angles to their motion and in the *counterclockwise direction.* The photographic

record in Fig. 7 shows the streamers deflected in the *clockwise direction,* and therefore the theory based on the postulates of positive ions or protons as the essential elements in the formation of the positive figure does not conform to the experimental evidence.

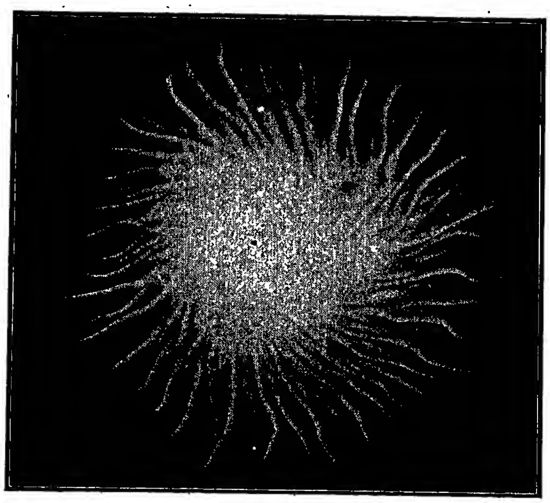

FIG. 15

Pressure 2.0 cm.; Gap 0.5 cm.; Field S, 12,300 cm². Electrode −; Paired with Fig. 14; Neg. No. 325.

Let the same argument be applied to the assumption that electrons falling towards the positive electrode are the active elements in the formation of the positive figures. Consider the direction of motion that an electron at the point a in Fig. 7 would have under the combined stress of the dielectric and magnetic fields;

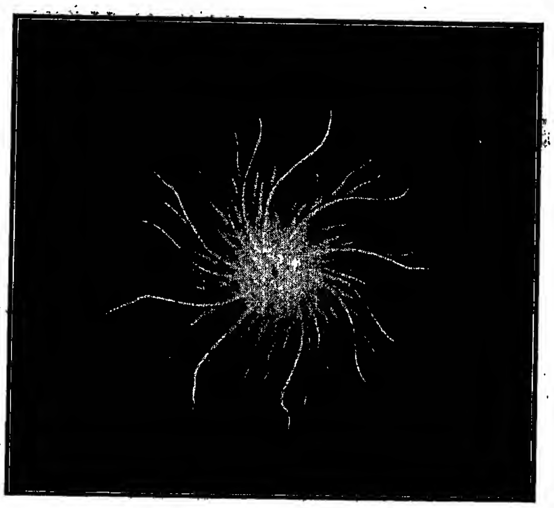

FIG. 16

Pressure 0.75 cm.; Gap 0.5 cm.; Field N, 12,600 cm². Electrode −; Paired with Fig. ..; Neg. No. 381.

the voltage gradient would cause the electron to fall radially towards the positive electrode, while the reaction of the magnetic field would be at right angles to the direction of motion of the electron and, as in the previous case, in the *counterclockwise* direction. The resulting curved path, (if the positive electrode is used as the point of reference), would be deflected in the *clockwise* direction; that is, in accord with the form of the streamers in Fig. 7.

Similar observations may be made for Fig. 9. In this case the magnetic field is in the S direction. The

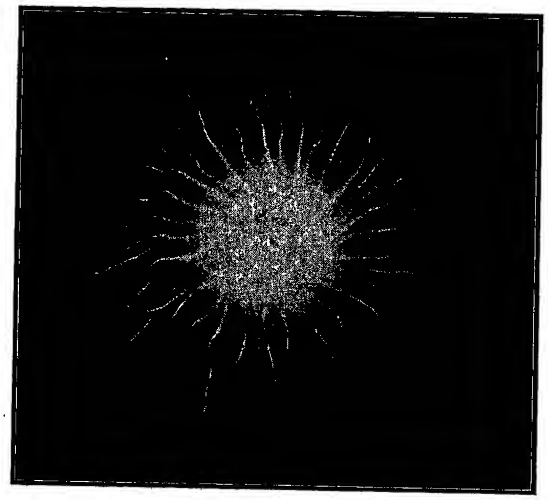

FIG. 17

Pressure 0.25 cm.; Gap 0.5 cm.; Field S, 12,500 cm². Electrode −; Paired with Fig. ..; Neg. No. 395.

reaction of the magnetic field on positive ion or proton at any point as a, Fig. 9, projected by the voltage gradient radially outwards from the positive electrode, would be a force at right angles to the direction of motion that would cause a deflection in the *clockwise*

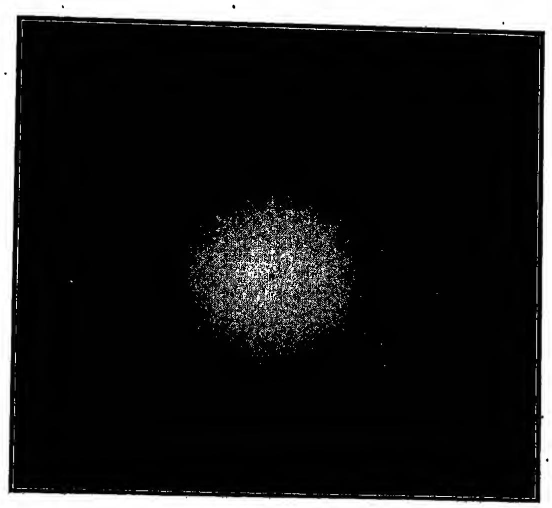

FIG. 18

Pressure 0.09 cm.; Gap 0.5 cm.; Field S, 12,500 cm². Electrode −; Paired with Fig. ..; Neg. No. 397.

direction. This is, however, in the reverse direction to that shown by the streamers in Fig. 9.

On the other hand, consider an electron at the point a in Fig. 9, under the stress of the voltage gradient, falling radially towards the positive electrode. The reaction of the magnetic field would be at right angles

to the direction of motion and in the clockwise direction. Using the positive electrode as the center of reference, the resulting path of the electron would be deflected in the *counterclockwise* direction. The theory based on the postulate of electrons falling towards the positive electrode as the active elements in the formation of the

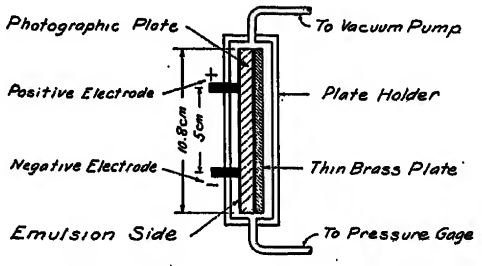

FIG. 19—LOADED PLATE HOLDER

positive figure is supported by the photographic records in Figs. 7 and 9.

To illustrate the explanation offered for the formation of both the negative and the positive figures, a diagrammatic representation of the voltage gradient waves and the direction of motion of the electrons with respect to both the positive and the negative electrodes is shown in Fig. 11. The diagram shows in cross-section of the holder with the two photographic plates, the brass plate and the positive and negative electrodes as when

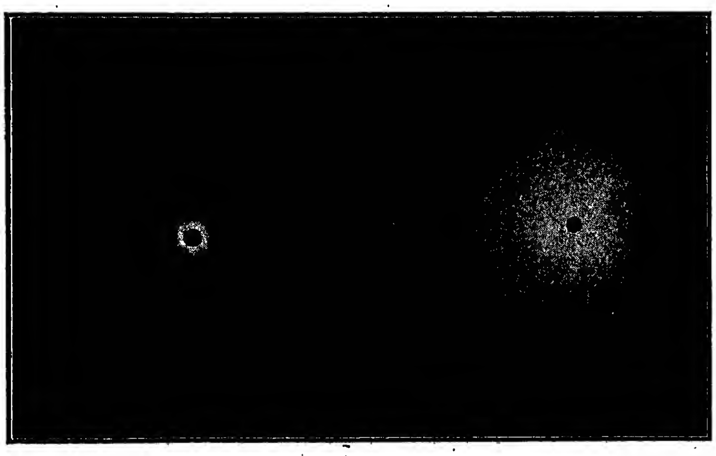

FIG. 20

Pressure 15.0 cm.; Gap 1.0 cm.; Field *N*, 12,500 cm².
Electrode −, +; Paired with Fig. . .; Neg. No. 394.

exposures were made for Figs. 3 to 10 and 12 to 18, inclusive.

The steep ionizing voltage gradient waves spread outwards from the two electrodes. From the negative electrode, a wave or stream of electrons is projected radially over the emulsion surface of the upper photographic plate. The negative figure is formed as the stream of electrons pass over the plate and as an after effect, the air near the surface of the plate becomes highly ionized.

An ionizing voltage gradient wave likewise travels outwards from the positive electrode over the emulsion surface of the lower photographic plate. The direction of motion of the electrons is, however, towards the electrode,—that is, opposite to the motion of the voltage gradient wave. It is also assumed that the positive streamers, or grooves, are paths of very low resistance and that therefore the voltage gradient will be of ionizing intensity for greater distances from the electrode than in the corresponding negative figure.

New Types or Forms of Lichtenberg Figures. In the presence of the magnetic field the range of air pressure within which Lichtenberg figures of definite form and structure can be obtained is greatly extended.

The lower limit of air pressure in which Lichtenberg figures, hitherto taken without the presence of the magnetic field have even a semblance of definite form and structure, is approximately 5 cm. Hg. At lower air pressures the figures lack definition and have the appearance of a nebulous haze or fog. Under the

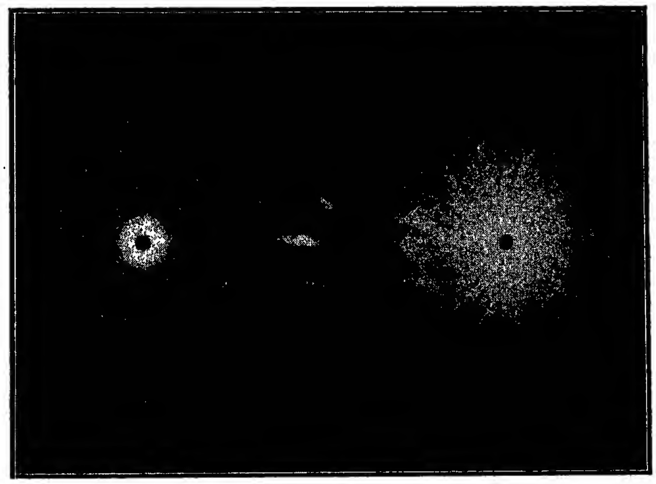

FIG. 21

Pressure 15.0 cm.; Gap 1.1 cm.; Field *N*, 12,500 cm².
Electrode −, +; Paired with Fig. . .; Neg. No. 393.

stress of the magnetic field the results are strikingly different; as evidenced by the photographs shown in Figs. 12 to 18, inclusive, figures of definite form and sharply defined structural details can be obtained at much lower air pressure. Special attention is called to Figs. 15 to 18 as being radically different in structure from the negative figures obtained at air pressures greater than 10 cm. Hg. The positive figures are weaker and not so well defined, but possess structural forms at much lower air pressures when under the stress of the magnetic field.

Both Electrodes on One Plate. For Figs. 20 to 24 inclusive, both electrodes were in contact with the emulsion side of a single plate. The arrangement of the electrodes, photographic plate, and brass plate, is shown in Fig. 19. By this method, both the positive and the negative figures produced by a single impulse are obtained on the same photographic plate. This arrangement has been used in attempts to determine

the nature of the figures themselves and in the study of related phenomena, such as sparkover[6] and breakdown of dielectrics, etc.; but when exposure is made under the stress of the magnetic field, the resulting figures acquire different forms that throw new light on the processes involved.

In Figs. 20 to 24 are shown a series of exposures

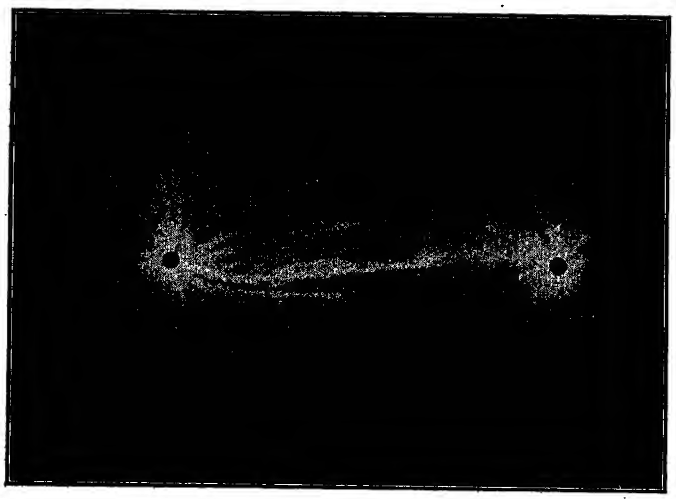

FIG. 22

Pressure 15.0 cm.; Gap 3.8 cm.; Field S, 12,300 cm^2.
Electrode −, + ; Paired with Fig. ..; Neg. No. 388.

showing positive and negative figures for progressively higher impressed voltages and correspondingly greater after effects. In order to correlate the more prominent features of the above figures let it be assumed:

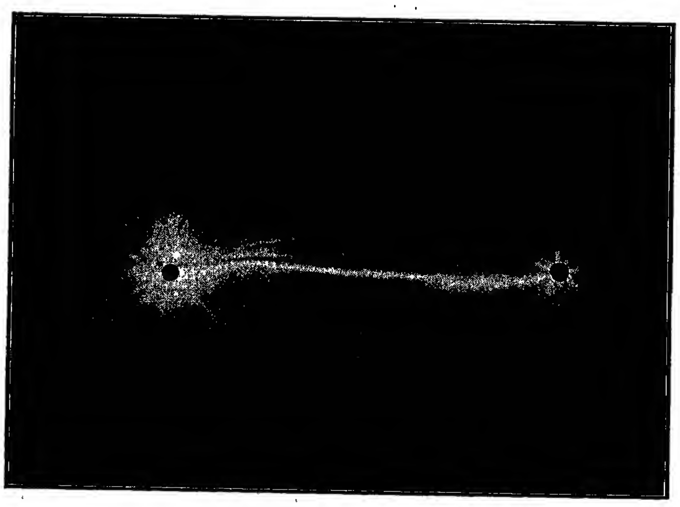

FIG. 23

Pressure 15.0 cm.; Gap 4.0 cm.; Field N, 12,500 cm^2.
Electrode −, + ; Paired with Fig. ..; Neg. No. 384.

(a) That the positive streamers or grooves are paths of high conductivity.

(b) That the space near to the negative figure, and especially near its periphery, is in a highly ionized state after the figure is formed.

(c) That the difference of potential between the two electrodes persists for some time after the Lichtenberg figures proper, have been formed.

The bending of the streamers in the positive and negative figures is in the same direction, using the

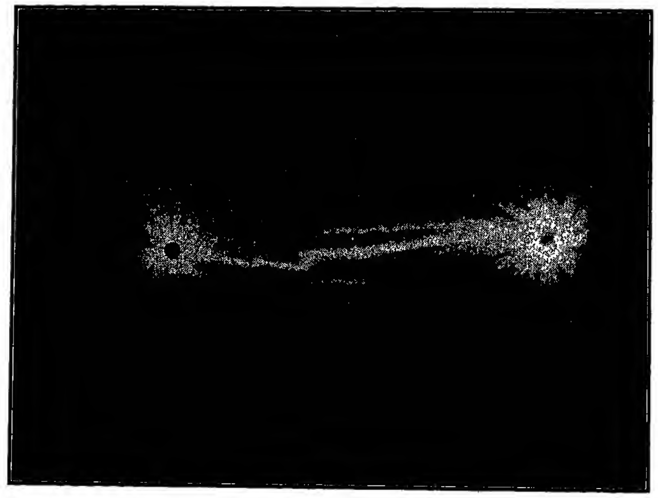

FIG. 24

Pressure 15.0 cm.; Gap 4.0 cm.; Field S, 12,500 cm^2.
Electrode −, + ; Paired with Fig. ..; Neg. No. 385.

electrodes as centers of reference. In Figs. 20, 21, and 23, the magnetic field was in the N direction and produced clockwise deflections in both the negative and the positive figures. For Figs. 22 and 24 the direction of the magnetic field was in the S direction and as a consequence, the streamers for both the positive and the negative figures show counterclockwise deflections.

In Fig. 20 the impressed voltage was barely sufficient

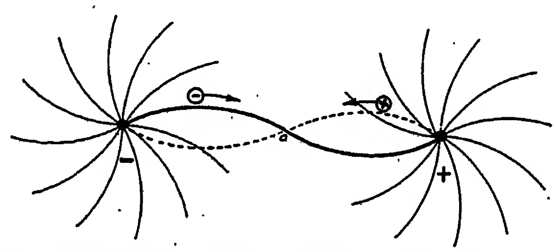

FIG. 25—DEFLECTIONS OF POSITIVE AND NEGATIVE STREAMER

to form a single connecting bridge or link between the two figures. In Fig. 21, with slightly higher voltage impressed, three paths bridge the gap between the two figures. Due to higher impressed voltages larger number of paths between the two figures is found in Figs. 22, 23, and 24. Each tuft or brush of light formed near the periphery of the negative figure is directed towards, and connected to, a prong or tip of a streamer in the positive figure. It should be noted that the brushes or paths bridging the space between the original

6. Erwin Marx, "Untersuchungen Uber den Elektrischen Durschlag und Uberschlag in Unhomogenen Felde," *Archiv für Elektrotechnik*, Vol. 20, 1928, p. 605.

Lichtenberg figures are apparently formed after the negative figure proper has been completed. This is shown most clearly in Fig. 21, but can readily be observed in Figs. 22, 23, and 24.

The tufts or brushes formed at the tips of the streamers in the positive figure, Figs. 21, 22, and 23, increase in size as the impressed voltage is increased. If sufficiently high voltage persists between the electrodes after the initial figures have been formed the gap between the electrodes is bridged by a sparkover as shown in Figs. 23 and 24.

The path of the sparkover, Figs. 23 and 24, between the two electrodes has sharp zigzag, lightning-like turns, superimposed on a basic double inflection, which in the main conforms to the deflections of the initially formed positive and negative figures. This indicates that the elements flowing in the sparkover channel are negatively charged; that is, the channel is formed by electrons attracted to the positive electrode and repelled from the negative electrode.

In Fig. 25 under the same conditions as in Fig. 23, the deflections of the positive and negative streamers are indicated by the curved lines extending from the electrodes as centers. It is evident that under the combined stress of the dielectric and magnetic fields, the path of the electrons coming from the negative electrode that pass through the point *a* and flow into the positive electrode follow the solid line curve as drawn in Fig. 25,—that is, in a path having a double deflection similar in form to the sparkover path in Fig. 23. On the other hand, positive ions or protons projected from the positive electrode under the same combined stress of the dielectric and magnetic fields, that pass through the point *a* and flow into the negative electrode, as in Fig. 23, must take a path as indicated by the broken line in Fig. 25; that is, a path having a double bend in the reverse direction to that of the sparkover in Fig. 23. If the same argument be applied to Fig. 24, a like conclusion will be reached, only it should be noted that since the magnetic field is in the opposite direction, the deflections would be in the reverse order. It appears, therefore, that electrons and not positive ions or protons were primarily the active elements in forming the sparkover channels in Figs. 23 and 24.

The bending of the streamers, due to the reaction of the magnetic field, increases with decreasing air pressure; but the rate of increase is greater for the positive figures than for the corresponding negative figures.

Several factors, such as the velocity of formation of the positive and negative streamers, the intensity and duration of the voltage impulse, the form of the voltage gradient waves, the strength and direction of the magnetic field, spacing of the field poles, the dimensions of plate holder, etc., enter into the problem of securing adequate experimental evidence for a quantitative analysis of the phenomena. The investigation will be continued as soon as the larger apparatus of more suitable design, now under construction, become available.

Discussion

H. A. Erikson: The paper prepared by Dr. C. E. Magnusson embodies results which show, it seems to me, in a conclusive manner that the electric transfer involved in the negative and positive discharges is negative in character. The compound character of the discharge line connecting the two pole centers and its directions of curvature are, it seems, conclusive on this point. This is a distinct accomplishment and is a step in advance.

Besides this, the results obtained present a number of features which, it is to be hoped, further research will clarify. For example, in the positive discharges at the lower pressures, why do the branches from the main trunk only pass from the convex side in the presence of the magnetic field? Also, why does the curvature reverse at the end of the positive streamer? Then there is a question as to how the photographic action is brought about. Is it due to the radiation produced as a consequence of the ionic recombination in the air close to the film?

It seems to me that Simpson's explanation of the lightning discharges* is extremely suggestive in connection with the results given in the paper. It would seem that the streamers in the positive discharge are due to what may be termed Simpson rockets, whereby at the head end, due to the intense field, ionization by collision takes place progressively from point to point and the resulting free electrons are discharged from the tail end. The positive ions so formed remain virtually stationary and through recombination give rise to the radiation to which the photographic action is due. The situation at the negative pole on this view is such that only the electron tail effect is in evidence.

C. M. Foust: Professor C. E. Magnusson's magnetic experiments with Lichtenberg figures are certain to result in a greatly improved understanding of the electrical mechanism whereby these figures are formed, and this improved understanding may have far reaching consequences for the following reasons:

1. Because Lichtenberg figures are one phase of our familiar corona phenomena and more extensive knowledge of the mechanism of corona will be helpful in many engineering problems.
2. Because Lichtenberg figures are made by surge voltages and surges are of vital importance in electrical design.
3. Because Lichtenberg figures are closely related to the surge voltage performance of insulation, and improved knowledge concerning the figures should promote better understanding of the surge breakdown of insulation.
4. Because a Lichtenberg figure is decidedly a gas phenomenon and electricity in gases is a subject of great interest to engineers.

The difficulties to be encountered in conducting experiments of this type are not obvious and Professor Magnusson has not called attention to them. The close association required between the high voltage necessary to produce the figures (several kilovolts) and the intense magnetic field required to deflect them makes the problem of insulating electrodes difficult. In addition partial vacuum must also be obtained and this, of course, introduces other problems.

The recent extensive use of Lichtenberg figures for measurement of surges on power systems has of course introduced questions regarding calibration, effect of wave shape, and arrangements of size and shape of electrodes. In Pedersen's comprehensive study as well as in the works of others it has been brought out that, while the size of the positive figure is practically independent of wave form, the negative figure varies in size with both the shape of the front and tail of the applied voltage wave. Also in view of general understanding that the velocity of formation of the positive streamer is considerably greater than that of the negative it would appear that the voltage distribution

*The Twentieth Kelvin Lecture, Journal of the A. I. E. E., Vol. 67, p. 82, (Nov., 1922).

between the positive and negative electrodes with the series arrangement shown in Figs. 2 and 19 would be determined by the shape of the applied voltage wave. The author's comments regarding these considerations and the wave shape used in his studies would be of interest.

Professor Magnusson's experiments and analysis suggest that the active elements in the formation of the positive Lichtenberg figures are electrons which move toward the electrode. As he points out this is contrary to Pedersen's conclusion which stated that the streamers were formed by protons moving away from the electrode. Certain characteristics of the figures shown suggest that both may be correct. Assume that immediately upon application of voltage, protons move away from the electrode at high but diminishing velocity and that they leave in their pathway a great number of free electrons which move toward the positively charged electrode. The electrons moving inward will be deflected from their radial pathway as shown in Fig. 25. Also the outward moving protons will be deflected at the streamer tips in the opposite direction as is observed in Figs. 7 to 9 and to some extent in all positive figures shown.

In Figs. 20 and 21 in this paper and many figures shown by Pedersen a decided bright glow is observed at the junction of positive and negative streamers. The assumption of charges of opposite polarity at streamer tips would appear to account for this much more satisfactorily than an assumption of like charges.

Professor Magnusson is to be congratulated on the painstaking perseverance with which he has pursued this investigation and future results from him will be of great interest.

George E. Quinan: While other experimenters have, I believe, produced the Lichtenberg figures under the influence of the magnetic field, the present paper is the first to point out the support given by this experiment to the hypothesis of Yoshida that the positive figures are produced by electrons being drawn into the positive electrode and not by moving positive ions.

This at once accounts for the characteristic positive streamers in that ionized channels of low resistance would be formed progressively outward following the receding front of the potential gradient, as illustrated in Fig. 11. It also accounts for the greater diameter of the positive figures since the low resistance paths afforded incoming electrons, permit ionization to proceed to a greater radial distance from the electrode.

Under the type of voltage gradient suggested in Fig. 11, the branches of the positive streamers are readily accounted for through the tendency of negative electrons to move into the positive ionized streamer channels in their immediate vicinity. Also, these branches under the influence of the magnetic field should join their stems with the same direction of curvature with reference to their junctures to the stems that the stems themselves have with reference to the positive electrodes. This would result in the branches coming into the stems from the convex side only, and this is what actually occurs. Fig. 9 is a good illustration of this.

The size of the Lichtenberg figures varies with the voltage and inversely with the atmospheric pressure. This has lent support in the case of the negative figures to the hypothesis that they are formed as a result of electrons being shot radially from the negative electrodes. Added support is now given this idea by the observed direction of bending in the magnetic field and by the fact that the degree of bending increases as the voltage decreases.

While these considerations lend support to the notion that electrons in motion are in some way responsible for the formation of the figures, it is by no means clear to the writer as to how certain important features of the figures can be thus accounted for. The sharply defined radial lines of the negative figures along which the photographic film has escaped the effects of the bombardment are not what one would expect from a discharge of mutually repellent particles. Neither are they easily reconciled with the notion advanced by some observers that the effect on the film is produced by a discharge from the film itself into the ionized space adjacent to its surface.

Quite as characteristic of these figures as their form is the difference between the positive and negative in brightness. The negative is characteristically bright, the positive dark. This suggests a radical difference in method of formation hardly explained by assuming a mere reversal in the direction of movement of the electrons.

Another difficulty arises from the fact that the negative figures frequently, as in Fig. 8, show concentric bands of different brightness with the outer bands brighter than those nearer the source of the assumed electronic shower. The negative figure in Fig. 8 has superimposed upon it as a result of oscillation, first a positive figure, then a negative figure of approximately the same diameter as the positive, next (presumably) a positive figure, which, however, is not distinguishable, and lastly another negative figure. The first negative figure is brightest, the second less bright, and the last one darkest of the three. This hardly seems consistent with the notion of three successive discharges of electrons from the central electrode.

The writer unfortunately has nothing constructive to offer in lieu of the suggestions advanced in Dr. Magnusson's paper and merely wishes to suggest that in continuing the experiments with the Lichtenberg figures the possibility of finding a more satisfactory fundamental hypothesis be not overlooked.

A Survey of Room Noise in Telephone Locations

BY W. J. WILLIAMS[1] and RALPH G. McCURDY[2]

Member A. I. E. E. — Member A. I. E. E.

Synopsis. This paper describes a survey made to determine the range of magnitudes of room noise present in telephone locations. Measurements were made in a total of 250 locations in New York City and environs, distributed among businesses and residences in accordance with telephone traffic distribution. In each location, measurements were made by a marginal audibility method using the human ear as a part of the measuring device, and by a visual indicating meter. A brief description is included of the apparatus employed with each of these methods. Results are presented for measurements made in various classes of rooms, under winter and summer conditions.

* * * * *

AMONG the projects of the Joint Subcommittee on Development and Research of the N. E. L. A. and Bell System is one (No. 4) which is studying the effects of noise[3] on telephone transmission and methods for its measurement. It was appreciated that, in addition to noises of electrical origin caused by exposures to power circuits or by sources incidental to the operation of the telephone system, there are also noises in the rooms in which telephones are used which have an important effect on telephone service. In studying the effects of noises, it is, of course, necessary to consider both noises of electrical origin and room noises. It was desired that, in laboratory tests of the effects of line noises on speech transmission, typical amounts of room noise should be provided at the test location. The survey described herein was made to obtain room noise data for these laboratory tests.

The methods described should be of general interest in connection with other noise problems. Increasing attention is being given, both in America and in Europe, to the general problem of noise as an undesirable attribute of modern civilization. Some efforts are being made to investigate sources of city noise. Modifications have been made in the design of machines and appliances, such as typewriters, motor cars, electric refrigerators, rotating electrical machinery, and domestic oil burners, so as to reduce the noise involved in their operation. Attention is being given to the quieting of rooms by means of acoustic treatment. Studies are being made of the effects of noise on living beings, including effects on the efficiency of workers.[4] In all of this work, quantitative measurement is important.

For the specific problem in hand, it was desired to obtain information on the magnitudes of room noise, as well as some general indication of the frequency composition of typical room noises.

While it is recognized that ordinary room noise is a highly variable quantity changing from instant to instant in loudness and frequency composition, it is felt that sufficient measurements were made to specify the makeup of a typical room noise for use in the laboratory tests, and in addition to obtain an indication of the effect of various factors, described below, upon the noise. Since it was desired to make the measurements as representative as possible of typical telephoning conditions, they were made at times of day and in types of locations determined by a study of telephone message traffic. Since the results would be affected by the choice of locations, they are presumably less typical for non-telephone than for telephone purposes.

The residences included in the survey ranged from apartments in large city buildings to small homes in outlying towns. In the business locations were included offices, stores, factories and workshops, and public buildings, such as hotels and clubs.[5] Establishments of various characters were included in each classification; they ranged in size from small stores to great manufacturing plants.

In making all measurements, an attempt was made to simulate the normal conditions which would obtain when a telephone call was placed. If noises existed in the room, which would be discontinued when the telephone was being used, such noises were stopped while the measurements were being made. On the other hand, care was taken to see that none of the normal noises of a particular location was discontinued because of the fact that measurements were being taken.

It was recognized that there would be a difference between the room noise experienced on local and on long-distance calls. The survey was made on the basis of telephone traffic as a whole, which consists predominantly of local calls.

The survey consisted of two series of tests, one made during the months of January, February, March, and April, and the other made during the months of July and August. The former series was the more compre-

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2. Development and Research Dept., American Tel. & Tel. Co., New York, N. Y.

3. In this joint work, noise is taken to mean any extraneous sound which would tend to interfere with telephone conversation.

Room noise is used to include any extraneous sounds at the place where the measurement is made, except those proceeding from the telephone receiver. It thus includes, in addition to noises such as the rattling of papers or the roar of street traffic, any other sounds extraneous to the telephone conversation, for example, those of other conversations or of music produced nearby.

4. D. A. Laird, "The Effects of Noise," *Jl. Acoustical Soc. Amer.*, Jan. 1930, p. 256.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

5. In public buildings, only a very small proportion of the telephone locations tested were in booths or at coin-box telephones.

30-110

hensive, including 205 measurements; the results given herein are based on this series of tests except where specifically noted otherwise. The second series of tests was made for the purpose of determining the difference between the room noise encountered under winter conditions and that encountered under summer conditions. Consequently, a selected group of the locations, which had been measured in the winter, were measured again under summer conditions.

It must be appreciated, in generalizing from the data given, that tests were made in only a limited number of locations.

Two methods were employed in making the measurements described in this paper, one electrical and the other aural. The electrical method employed a condenser-transmitter pick-up, amplifiers and detector. A weighting network was incorporated in the amplifier to simulate the sensitivity characteristic of the ear. The aural method, known as the "masking method," involved the measurement of the masking effect of the noise on various warbler tones recorded on a phonograph record. Both of these methods will be described in greater detail below.

General Results

Some of the interesting results which were obtained from this survey may be summarized as follows:

On the average, room noise in residences was about 20 db. less in magnitude than that in business locations.

The spread in the magnitudes of business room noises was about 40 db., as compared to 20 db. for residence room noises. These spreads include 90 per cent of the measurements, excluding the lowest and highest 5 per cent. The standard deviation of the measurements was about 12 db. for business noise and 6 db. for residence noise.

Room noises average 4 or 5 db. higher in summer than in winter.

In general, the magnitude of residence noise was affected to only a minor extent by the size of the town or city in which it was measured.

On the average, the frequency composition of residence noise was about the same as that of business noise. The masking effect of the noise on a tone covering the range 750-1500 cycles was greater than that on ranges above and below this. The magnitudes of components in the lower part of the range covered (about 250-5000 cycles) appeared to be somewhat larger than those in the higher part of this range.

Methods of Measurement

The two methods which were employed in the survey are as follows:

Aural Method—Masking of Warbler Tone.[6] In this method a tone of varying pitch (warble) is produced and sent into a receiver. The receiver cap is provided with slots shaped so that the observer's ear canal is always open to the air of the room regardless of how firmly the receiver is pressed against the ear. The tone is generated by means of a phonograph record and a magnetic phonograph record pick-up, and is a variable-frequency tone, the pitch of which varies between certain limits several times per second. An attenuator is placed between the magnetic pick-up and the receiver. The observer sets the attenuator at a point where he can barely recognize the sound of the warble in the presence of the room noise. He also obtains the setting at which he can barely hear the warble in a perfectly quiet room. The difference between these two settings is a measure of the masking effect of the noise in this room upon the warbler tone, for this particular observer.

An idea of the frequency composition of a given room noise may be obtained by using several different warbler tones, each covering a different portion of the voice-frequency range. This is based on the fact that, in general, a tone of a given frequency masks to a greater extent tones that are near it in frequency than tones that are far removed from it in frequency.

The phonograph records used in the present room noise survey were three-band records, *i. e.*, three warbler tones were cut on each record, each tone occupying about one-third of the available space. The frequencies included in the various bands were as follows: high band, 1500-5600 cycles per second; middle band, 750-1500 cycles per second; low band, 250-750 cycles per second. In each band the frequency varied continuously from the lower to the upper limit and back to the lower limit, the period of such a complete "warble" being about one-sixth of a second.

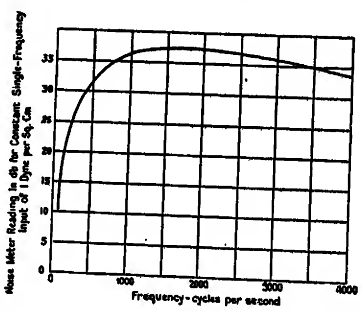

Fig. 1—Response Characteristic of Room Noise Meter

Electrical Method—Room Noise Meter. There is, of course, a number of different electrical methods which might be employed for measuring room noise, ranging from a single over-all measurement to a complete wave shape or frequency analysis. The complete analysis or the measurement of energy present in a considerable number of narrow frequency bands is subject to the disadvantages, for such a survey as this, of slowness of measurement and bulkiness of testing equipment.

The method which was adopted was one based on the use of a frequency weighting simulating the sensitivity of the ear. This frequency characteristic is shown on Fig. 1. It is an equal loudness weighting; that is, the room noise meter was so constructed that different

6. R. H. Galt, *Jl. Acoustical Soc. Amer.*, October 1929, p. 147.

single-frequency noises of equal loudness would give approximately the same meter readings. The shape of an equal-loudness curve is somewhat flatter for high levels of loudness than for low ones. The weighting curve chosen for the meter was for a loudness corresponding to that of a 1000-cycle tone 30 or 40 db. above the threshold of audibility. This general level is not far from the middle of the range of levels of room noise components. The loudness data used were those given

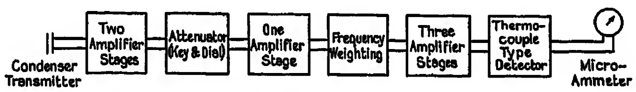

FIG. 2—SCHEMATIC DIAGRAM OF ROOM NOISE METER

by Kingsbury,[7] based on experimental data on single-frequency tones.

The sensitivity of the meter is such that a 1000-cycle tone about 28 db. above threshold would give a reading of 0 db. on the meter scale.

The room noise meter employed is shown together with its auxiliary equipment in Fig. 3. It consists of a condenser transmitter for converting acoustical energy into electrical energy, six stages of amplification for raising the level of the noise currents sufficiently to operate a thermocouple meter indicating device, and a weighting network, as described above, as well as certain apparatus not employed in obtaining the results reported here. The general layout of the circuit is indicated in the schematic diagram of Fig. 2. A portable battery supply and means for calibrating form the necessary auxiliary equipment. An adjustable attenuator controlled by a key and a dial is provided between stages of the amplifier so that the noise energy being measured may be brought within the range of the meter over a range of levels of 80 db. (corresponding to a power range of 100,000,000 to 1).

Operation of the Room Noise Meter. The noise meter is first calibrated, as described below, so that its sensitivity is set at a predetermined value. The condenser transmitter is then placed at the spot where it is desired to measure noise, and the gain of the amplifier is adjusted by means of the key and dial until the needle of the microammeter in the output circuit fluctuates about a given point. The settings of the key and dial then give a measure of the noise. In addition to the average readings obtained in this manner, readings of the fluctuations in the noise can be similarly obtained. As an aid in the reading, the microammeter scale is calibrated in decibels.

The calibration of the meter in the field consists of a check on the over-all sensitivity of the instrument. The filament currents and plate voltages are adjusted to the correct values. Then a fixed percentage of the electrical output of a standard buzzer, the current from which is measured by a thermocouple, is fed into a special receiver which is placed in a prescribed way on the condenser transmitter. The gain of the amplifier is then adjusted until the output microammeter needle reaches a predetermined point. The sensitivity of the meter will then be as shown on Fig. 1.

An over-all calibration of the meter, as a function of frequency, is given on this figure. To obtain this, separate determinations were made of the volts generated by the condenser transmitter per unit of pressure, and the meter reading per volt generated by the transmitter, as a function of frequency; and the results were combined to give the values shown. Harmonics in the testing waves were reduced to such a point that they did not affect the results. After a substantial part of the survey had been completed, a check was made of the electrical portion of the calibration, and the changes found were quite negligible.

Accuracy of the Meter. The precision of the apparatus is substantially greater than the precision with which ordinary varying noises can be measured. The readings obtained for steady inputs are proportional to the input, with an error of less than ½ db., over the entire range of noise amplitudes found in the survey. The apparatus is shielded electrically. In only one case did electrical fields produce any observed errors in the readings; this was when an attempt was made to measure the room noise near a rotary converter in a power station. The vacuum tubes are mounted in such a way that the effects of ordinary mechanical vibration on the readings are negligible.

Comparison of the Two Methods. In general, the meter method gives results in physical terms while the

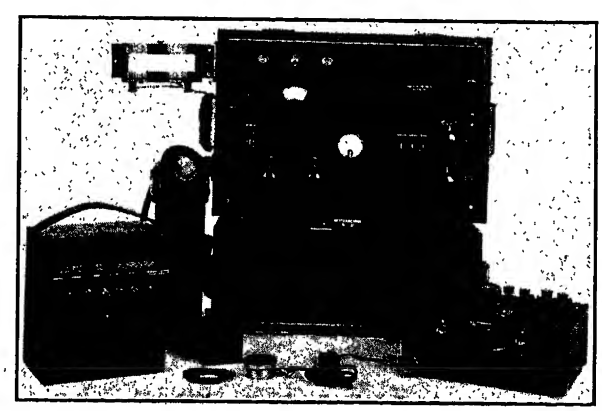

FIG. 3—ROOM NOISE METER AND AUXILIARY EQUIPMENT

masking method gives them in terms of effects on the ear; consequently, the choice of the method to be employed in any particular case depends somewhat on the use to which data will be put. It is true that the meter includes a network to simulate the sensitivity of the ear for various frequencies; it does not, however, simulate other properties of the ear, such as the departures from linearity in response by which subjective tones are produced by the ear mechanism, and the

7. *Physical Review*, Vol. 19, April 1927, pp. 588-600.

complicated way in which one sound masks another.[8]

The meter method, unlike the masking method, avoids any errors due to variations in human ears. This advantage is offset to some extent by the fluctuations of the meter needle, which makes it difficult to obtain the mean reading if the noise is unsteady as is the case with most room noises.

In the case of noises of a distinctly intermittent,

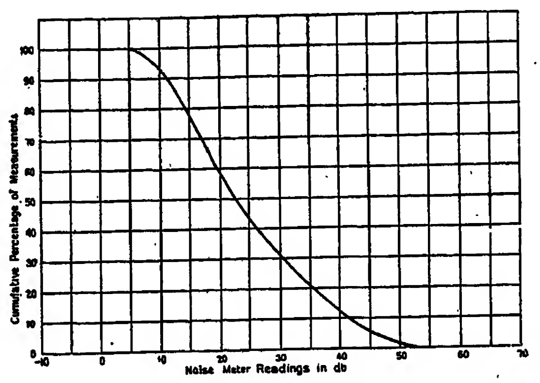

FIG. 4—RESULTS OF NOISE METER MEASUREMENTS OF NOISE IN BUSINESS LOCATIONS

staccato character, the warbler tone can be heard and recognized in the brief intervals when the noise is a minimum. A preliminary investigation showed that, for a noise of this sort, the relation between readings obtained by the masking method and by the meter method was different from the relation obtained for a steady noise, the warbler readings being relatively lower in the case of intermittent noise.

Both methods were used in the survey, because it was felt that each gave information which could not be as accurately obtained from the other, and also because the use of two methods enabled each one to be used as a check upon apparatus defects which might occur in the other.

In using the masking method, data were taken by two experienced observers and corresponding measurements averaged. All meter measurements were made by one observer.

RESULTS OF SURVEY

Noise in Business Locations. One hundred and nine business locations were visited. The magnitudes of the noises measured varied from that found in a doctor's quiet office to the din of a large manufacturing plant. Distribution curves for the noises measured are shown in Fig. 4 for the meter method and Fig. 5 for the masking method. For any point on one of these curves the corresponding per cent of all of the measurements made had values equal to or greater than the indicated abscissa value.

It may be seen that with the exception of the "high" curve of Fig. 5 the curves for meter and masking methods are fairly similar in shape. The "middle" curve has been selected to represent the masking method.

If there are excluded as extremes those noises which were so low that 95 per cent of all the noises measured equaled or exceeded them, and those which were so high that only 5 per cent of the measurements equaled or exceeded them, the spread of noise magnitudes is seen to be about 40 db. The standard deviation of the measurements is about 12 db.

As shown on Figs. 4 and 5 the median business room noise would produce a reading of 23 db. on the meter scale and a masking of 27 db. on the high-frequency warbler tone, 39 db. on the middle-frequency tone, and 31 db. on the low-frequency tone. The average business room noise was about 2 db. higher than the median.

Some conception of the amounts of noise represented by these figures may perhaps be gained from the following. The extremely loud noise measured in a local station of the New York subway while an express train was passing produced a meter reading of 70 db., while the lowest noises measured in the survey, in quiet residences, gave readings near 0 db.

Data on noise at the business locations tested have been grouped so as to show the average differences in the room noise values obtained for different types of business and for different sizes of towns. It will be appreciated that only a very small number of measurements were included in each sub-classification, and that consequently it is not safe to generalize from these sub-groupings as to room noise conditions in general.

Averages of the room noise measurements for the

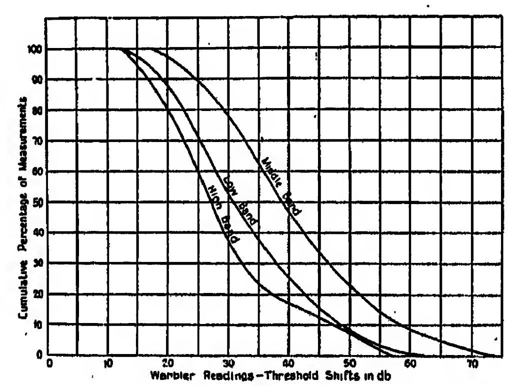

FIG. 5—RESULTS OF MEASUREMENTS OF NOISE IN BUSINESS LOCATIONS BY MASKING METHOD

different types of business locations are shown in the following table:[9]

8. R. L. Wegel and C. E. Lane, "Auditory Masking and Dynamics of the Inner Ear," *Physical Rev.*, Feb. 1924.

9. It will be noted that in the results given, the difference between the masking of the middle-frequency tone and the meter reading is relatively constant. It was found that for any considerable sub-group of the measurements, this difference was not far from 15 db. This figure, of course, would not in general hold for a single noise selected at random. There was a general tendency for the difference to be somewhat larger for larger values of noise.

Type of business location	Masking of middle-frequency tone	Meter reading	Number of measurements
Offices	42 db.	24 db.	34
Stores	34	18	34
Factories	57	40	18
Public buildings	35	21	23
Average of all businesses (weighted according to number of measurements made)	40	25	109

The above figures show a significant difference between the noise measured in factories and that measured in other types of location. The other differences shown were found not to be significant when examined in the light of the spread in values for individual locations in each class.

Averages of the business room noise measurements obtained in various sizes of towns are shown in the table below.

Size of town	Masking of middle frequency tone	Meter reading	Number of measurements
Class A (over 400,000 pop.)	45 db.	26 db.	39
Class B (100,000 to 400,000 pop.)	37 "	22 "	18
Class C (10,000 to 100,000 pop.)	42 "	27 "	41
Class D (less than 10,000 pop.)	27 "	11 "	11

These figures indicate that (with the exception of Class C towns) the business noise measured in large cities was greater than that in smaller towns. This is believed to hold true despite a fairly large spread in individual measurements within a given class. The exception in the case of Class C towns is explained by the fact that a fairly large percentage of the measurements in this class were made in large factories.

Room noise in business locations was observed to be quite complex in frequency composition. The masking effect of the noise on the middle band was greater than that on the high and low bands. In order to give an approximate interpretation of this in terms of pressures in various frequency regions, account must be taken of the relative magnitudes of threshold pressures in the three warbler frequency bands, since the masking effects were obtained by subtracting threshold settings of the attenuator from the settings made in the presence of the noise. For the middle and upper bands, threshold pressures are about the same; hence, the lower values of masking for the high range indicate that components in this range are in general relatively weak. As previously determined,[10] threshold pressures at frequencies in the low band are several decibels higher than those in the other bands. Combining the values of masking for the low and middle bands with the corresponding threshold pressures, it is seen that the physical magnitudes of components in the low- and middle-frequency ranges are in general not far different. The above analysis is, of course, very rough, as the whole range from 250 to 5600 cycles is divided into only three bands.

10. H. Fletcher, "Useful Numerical Constants of Speech and Hearing," *Bell System Tech. Jl.*, July 1925.

Room Noise in Residence Locations. Measurements were made in 96 residence locations.

Figs. 6 and 7 show distribution curves for these measurements. Compared with the corresponding measurements made in business locations it is apparent that the room noises encountered in residences were not only much smaller in magnitude but also varied less in magnitude than business room noises. The average of the residence room noises is about 18 db. less than the average of the business room noises, while the spread in residence room noise (using the 95 per cent and 5 per cent points on the curves as limits) is 20 db., compared to 40 db. for business noise; the standard deviation of the residence measurements is 6 db., compared to 12 db. for the business measurements. Unlike the curves for business noise, the curves for residence noise are very symmetrical, showing similar distributions above and below the average values.

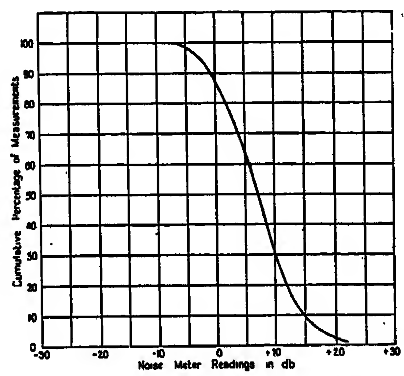

Fig. 6—Results of Noise Meter Measurements of Noise in Residence Locations

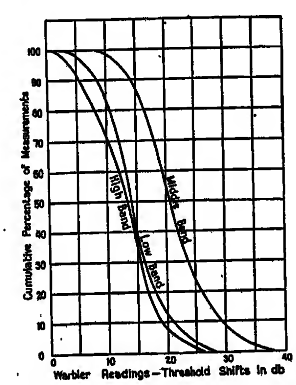

Fig. 7—Results of Measurements of Noise in Residence Locations by Masking Methods

As shown on Figs. 6 and 7, the median residence room noise would produce a reading of 7 db. on the meter, and a masking of 12 db. on the high-frequency warbler tone, 20 db. on the middle-frequency tone, and 13 db. on the low-frequency tone. The average was about the same as the median.

The average of the room noises measured in single-family houses was practically the same as the average of the noises measured in apartments.

Averages of the residence room noise measurements obtained in towns of various sizes are shown in the following table:

Size of town	Masking of middle-frequency tone	Meter reading	Number of measurements
Class A (over 400,000 pop.)...	20 db.	7 db.	33
Class B (100,000 to 400,000 pop.)...	20 "	8 "	14
Class C (10,000 to 100,000 pop.)	23 "	6 "	37
Class D (less than 10,000 pop.).	17 "	7 "	12

It will be observed from this table that the residence noises measured in large cities were no greater than those measured in smaller towns. A study of the data showed that 27 of the 33 measurements made in Class A towns were made in residences which would be classed as apartment houses. It is possible that the noise usually associated with big cities is confined chiefly to non-residential locations, and that apartments on side streets are no noisier than residences in smaller towns. It should be recalled, however, that the number of measurements in each class of town was very small. In any case the data tend to show that the difference between residence noise in the large city and that in the smaller town probably is not extremely large. The measurements for Class A cities were made chiefly in Manhattan and Brooklyn with a small number in Newark.

It was found, in a manner similar to that discussed above for business noise, that the average residence room noise was quite complex in frequency makeup, and apparently did not differ materially from the average business noise in the relative amplitudes of low and high frequencies.

Comparison of Room Noise in Winter and Summer. Forty locations were visited both in summer and in winter and the data compared. It was found that both business and residence noises were somewhat greater in summer than in winter, the average difference being 4 or 5 db. The spread in values obtained under summer conditions was less than that found for the winter conditions. This was because the noises which showed the least magnitude, when measured in winter, were found to be higher under summer conditions, while the highest noises measured failed to show an appreciable change with season. These highest noises were largely caused by indoor machinery, and would not be appreciably modified by outside sources.

The average frequency composition of the noises measured under both summer and winter conditions seemed to remain about the same as far as could be determined.

Selection of Typical Room Noise and Its Reproduction

The data obtained have been used in determing the characteristics of a typical room noise to be recorded on a phonograph record and reproduced for use in laboratory tests.

Since the data revealed no difference between the average frequency composition of great and small noises, it has been possible to choose a single recorded noise and to vary merely the amplitude of the reproduced noise, keeping its frequency makeup constant.

The recording and reproduction of such a noise have presented problems, particularly from the point of view of naturalness. It has been found difficult to reproduce a noise by simple means in such a way as to give the illusion that the noise is real, not artificial. The requirements for reproducing a noise which will be typical in its effect on the intelligibility of speech transmitted over telephone circuit are, however, considerably less severe than those for obtaining naturalness. Three main factors seem to be involved in the problem. In the first place, room noises often contain high-frequency components, undoubtedly including some extremely high frequencies. These components, while they are generally of low energy content, seem to contribute substantially to the naturalness of the sounds. The effect of these components on the intelligibility of speech transmitted over a telephone circuit would, however, be much less than their contribution to the

LIST OF TOWNS WHERE ROOM NOISE SURVEY MEASUREMENTS WERE MADE

Size of town	Name of town	Number of measurements: Business		Number of measurements: Residential	
Class A (over 400,000 pop.).	Brooklyn, N. Y.	7		18	
	Manhattan, N. Y.	32		13	
	Newark, N. J.	0		2	
	Total		39		33
Class B (100,000 to 400,000 pop.)	Jamaica, N. Y.	11		11	
	Yonkers, N. Y.	7		3	
	Total		18		14
Class C (10,000 to 100,000 pop.)	Bloomfield, N. J.	0		2	
	East Orange, N. J.	7		9	
	Flushing, N. Y.	0		5	
	Harrison, N. J.	3		0	
	Kearny, N. J.	6		0	
	Maplewood, N. J.	6		10	
	Milburn, N. J.	4		1	
	Mt. Vernon, N. Y.	6		4	
	New Rochelle, N.Y.	0		2	
	Orange, N. J.	4		0	
	Summit, N. J.	2		2	
	West Orange, N. J.	3		2	
	Total		41		37
Class D (less than 100,000 pop.)	Hollis, N. Y.	6		7	
	Madison, N. J.	0		3	
	Pelham, N. Y.	3		1	
	Richmond Hill, N. Y.	2		1	
	Total		11		12
	Grand total		109		96

naturalness of the noise, since the transmitted speech is generally limited to a band of not more than 3000 cycles. The frequency band transmitted by the recording and reproducing system was nearly twice this amount, being limited both by the mechanical characteristics of the apparatus and by the unavoidable noise generated in this apparatus, the amount of this noise increasing as the band width increases. Second, room noises emanate from a considerable number of sources located in different positions, so that in order to reproduce them with complete fidelity each source must be reproduced separately in its own position. On account of binaural effects in hearing, the proper locating of sources seems to have a considerable effect on naturalness. The most practical method of securing an approximation to this effect in the reproduced noise is to dispose a number of loudspeakers in different places in the room, chosen by test so that false directional effects are avoided. Third, the effects of reverberation must be considered. A noise picked up in a highly reverberant room, and reproduced in another highly reverberant room, would have in it two sets of reverberations. The best method of taking care of this seems to be to make artificial adjustments in the reverberation in the two rooms. Finally, there is a residual effect due to the fact that a person experiencing an actual noise is aided in his recognition of the noise by visual and other factors enabling him to refer it easily to its source; these are, of course, not present when the sound is reproduced.

Conclusions and Acknowledgment

While a certain amount of work on room noise conditions in telephone locations had been previously carried out, this survey represents a considerable advance in knowledge of room noise magnitudes. It provides data for work on the effects of noise on telephone transmission, as well as furnishing certain information of wider interest. The methods of measurement employed, when further developed in the light of the experience gained in this work, should prove valuable in other room noise investigations.

The authors wish to acknowledge the work of Messrs. J. W. Whittington and R. E. Philipson of the National Electric Light Association and Messrs. J. M. Barstow and R. S. Tucker of the American Telephone and Telegraph Company, in designing and building the room noise meter and in carrying out the survey.

The 220,000-Volt System
of the Hydro-Electric Power Commission of Ontario

BY E. T. J. BRANDON*

Fellow, A. I. E. E.

Synopsis.—Power requirements of the Commission's 25-cycle Niagara System are outlined. Preliminary studies in connection with the choice of transmission voltage, location of terminal transformer station, etc. are discussed, together with the technical studies involved in the design of a system for transmitting 260,000 hp., 230 mi. at 220,000 volts, and transforming same at the receiving end, for interconnection with the existing 110,000-volt system.

The Toronto-Leaside 220,000-volt transformer station is described, including the 220,000-volt switching arrangement, 45,000-kv-a. three-winding transformer banks, 110,000- and 13,200-volt switching arrangements, 25,000-kv-a. vertical-shaft out-door synchronous condensers, relaying, communication, and control.

The 220,000-volt transmission system is also described, including the use of aero-photography in surveying the route and locating the towers, design of supporting structures, details of conductor supports, insulation, ground wire practise, etc.

The paper concludes with a résumé of operating experience on the 220,000-volt system to date, and an outline of the future development of the system as at present anticipated.

* * * * *

Introduction

The Niagara System of the Hydro-Electric Power Commission of Ontario is the major system of the Commission, covering an area of some 12,000 sq. mi. in the south westerly portion of the Province, adjacent to the shores of Lakes Ontario and Erie. This area, roughly rectangular in shape, extends from the municipalities situated on the Detroit and St. Clair Rivers on the west, to the metropolitan area of Toronto on the east, a distance of some 230 mi.

With the exception of several large electrochemical and metallurgical customers located in the immediate vicinity of the Niagara River, the power demand on this system comes from some 371 municipalities, ranging in size from the City of Toronto to the small villages and rural districts.

Previous to October 1928, this "Municipal" load was supplied entirely from the Commission's generating stations located on the Niagara River, over a network of approximately 1200 circuit miles of 110,000-volt transmission lines. There were nineteen 110,000-volt transformer stations varying in capacity from 90,000 kv-a. to 3750 kv-a.

Commencing in October 1928, due to the fact that generation on the Niagara River had reached the limit dictated by the International Treaty regarding water diversion, power to supply the increasing demand was purchased under contract. A block of 260,000 hp. was purchased from the Gatineau Power Company, supplied from its generating plants located on the Gatineau River in the Province of Quebec, some 230 mi. to the east of Toronto, and transmitted over the Commission's transmission lines from the interprovincial boundary, for interconnection with the Niagara System.

It is the object of this paper to present some of the problems brought up by this interconnection, particularly as they affected the fundamental plan for the supply of power to metropolitan area of the City of Toronto.

History of System Growth

The growth of the annual peak load on the Municipal System from December 1922, one year after the placing into operation of the Commission's Queenston-Chippawa generating station at Niagara Falls, to December 1929, is shown in Fig. 1. It will be noticed that at the end of this period the annual increment was of the order of 50,000 kw. This figure becomes 75,000 kw. if the increment on the remainder of the Niagara System is included.

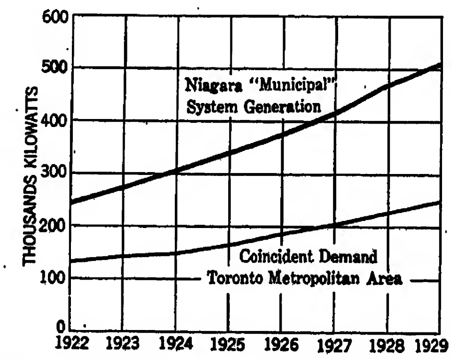

Fig. 1—Growth of Annual Peak Loads

The growth of the annual peak load in the metropolitan area of the City of Toronto is also included in Fig. 1. It will be noticed that the Toronto load represents nearly one-half of the Municipal load, having an annual increment at the end of the period of the order of 25,000 kw.

Referring to Fig. 2, the original station of the Commission in Toronto is that marked as Strachan Transformer Station. A double-circuit transmission line was brought into the city, paralleling the shore of Lake Ontario, and the station was located approximately two miles from the business center of the city. The growth of the city at that time was largely to the west and

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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north west, being somewhat limited to the east by the barrier of the Don River Valley.

In 1918, a second smaller station (York Transformer Station) was constructed west of the city, primarily to serve the suburban industrial load in that area.

In 1921, with the taking over of a competing power company, a private right-of-way to the north was acquired, and adjacent to it, two new transformer stations were constructed and placed in operation in 1924. These stations are marked as Wiltshire Transformer Station and Bridgman Transformer Station.

At this time, the distribution of load was such that these three city stations were spaced almost equally around the center of gravity of the load and at three-mile centers,—an almost ideal arrangement. Power was supplied over four 110,000-volt circuits, with a double-circuit infeed at 90,000 volts from the acquired power company's station forming a peak supply. In December, 1926, the installed capacities were—Strachan 90,000 kv-a.; York 15,000 kv-a.; Wiltshire

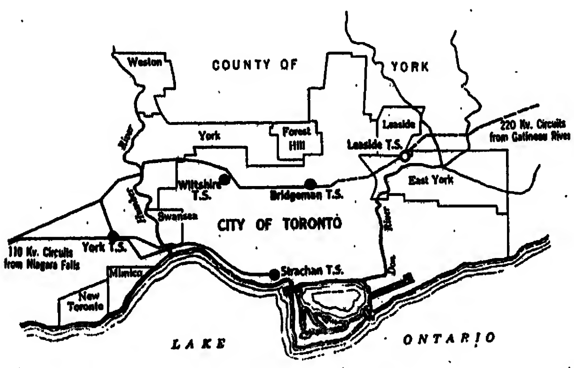

Fig. 2—Toronto and Vicinity, Showing High-Voltage Transmission Lines and Stations. December 1929

45,000 kv-a.; and Bridgman (including the 90,000-volt capacity) 78,000 kv-a.

In the meantime, the barrier of the Don River Valley had been broken down with adequate viaducts, and a rapid residential growth to the east had taken place. By 1926, the load demand of the area had increased to the point where the necessity of a fifth 110,000-volt transformer station, located to serve that area, was indicated.

It was at this time that the contract with the Gatineau Power Company was entered into, and Toronto, being at the easterly limit of the then existing System, and representing approximately one-half the System load, was chosen as the point at which the necessary interconnection would be made. The problem of additional transformer stations became merged, therefore, with the problem of devising a plan whereby this new source would be incorporated with the existing system.

At this point it should be mentioned that the Hydro-Electric Power Commission does not distribute power throughout the city. The Commission is responsible for transmitting power to the city and providing for its transformation to distribution voltage,—in this case 13,200 volts. At this point, the power is delivered to the local Commission, (in this instance, the Toronto Hydro-Electric System), for distribution to the ultimate consumer. This paper, therefore, deals only with the main transformer stations, and not with the 13,200-volt, (or lower) distribution system.

Load Analysis and Location of Station

Coincident with the carrying on of negotiations for the supply of power from the Gatineau Power Company, economic studies were carried out to decide on the transmission voltage to be adopted. Calculations were carried out at 110,000 volts, at 220,000 volts, and at two intermediate voltages. As the power was to be purchased at the transmission voltage, studies included estimates of the cost of transmission, transformation at the receiving end where required, and tying in with the existing system, and also included a range of sizes of transmission conductors, so as to arrive at the most economical conductor for each voltage.

In addition to the purely economic comparison, consideration was also given to such factors as service security, the multi-circuit system economically possible at 110,000 volts ordinarily providing a greater degree of service security than a two-circuit 220,000-volt system; the relative immunity of the different types of construction to flashover, it being expected at that time that lines of higher voltage might be more susceptible to such occurrences; the control of charging kv-a. on the 230-mi. circuits, though the frequency, being 25 cycles, rendered this less of a problem than on other systems operating at 50 or 60 cycles.

As a result of these studies, a nominal transmission voltage of 220,000 volts was adopted, a transmission system of two circuits of 795,000-cir. mil. A. C. S. R. being decided upon as the most economical arrangement.

The decision to adopt 220,000-volt transmission gave a preliminary conception of a system layout. It was thought at this time that transformer stations operating at this voltage should be kept well outside urban areas, as the insulation problem was not yet regarded as solved. Dirt and smoke incidental to urban areas were therefore to be avoided.

The first arrangement located the 220,000-volt station north and east of the city limits, and it was proposed to step-down at this point to 110,000 volts, transmitting the power into the city at this voltage. One of the stations to be supplied in this manner was to be the fifth station previously mentioned as being desirable east of the Don River Valley. The necessary synchronous condensers were to be operated from the delta-connected tertiary windings.

A more detailed analysis of the load division in the metropolitan area of the city than had been made heretofore was undertaken, with a view to establishing

economic station locations, and at the same time, to form the basis of stability studies which it was intended to undertake later.

Fig. 3 shows the distribution of load in the metropolitan area of the city in thousands of kv-a. per sq. mi. as determined in December 1926. The figures represent the arithmetic sum of the peaks of the various classes of load in the separate square miles, but it has been calculated that the same figure also represents the coincident peak demand in horsepower, and may be used as such when obtaining station capacity.

The maximum demand per sq. mi. was in the downtown business area, approximately 15,500 kw. coincident. Residential districts had demands varying between 2600 and 3300 kw. per sq. mi. There were 11 sq. mi. having commercial power loads alone in excess of 2500 kw. The average for the 76 sq. mi. covered was 2450 kw. per sq. mi. coincident.

From these figures of actual distribution, an attempt was made to estimate the load in the respective square miles for the years 1930, 1933, and 1936. The peculiar

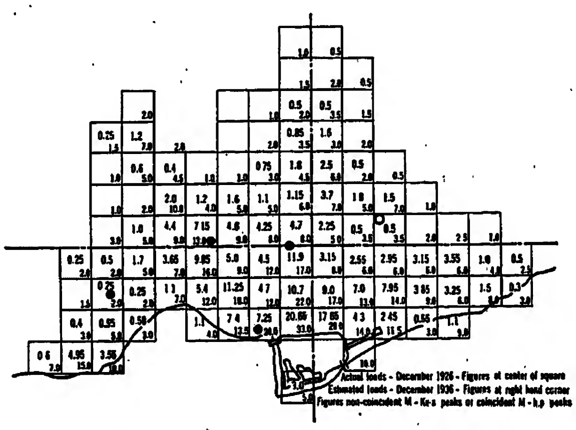

Fig. 3—Toronto and Vicinity—Load Distribution per Square Mile

condition of each unit was considered,—whether business, manufacturing, or residential, whether rapidly growing or near apparent saturation, whether affected by natural barriers, etc.—and an attempt was made to estimate the growth accordingly. The distribution arrived at for 1936 is also shown in Fig. 3.

The maximum down-town square mile was increased to 25,000 kw., while the average for 98 sq. mi. was increased to 4800 kw., both coincident.

A resurvey of the distribution has recently been completed, and shows that the figures for December 1929 are in very close agreement with those estimated. Since the original survey was completed, the data have been so useful that arrangements have now been made to bring the record up-to-date annually.

Alternative sites for transformer stations were selected; and economic dividing lines between these sites and existing stations were drawn, the object being to plan a 110,000-volt distribution system in which each station would be so located as to be as near its load center as possible.

These studies brought out the possibility of locating the new 220,000-volt station so as to supply 13,200-volt power directly, utilizing the delta tertiary windings which were to be included in any event. The increase in the cost of the transformers would be relatively small, which would allow practically the whole of the cost of the second transformation, from 110,000 volts, to be utilized to extend the limits of 13,200-volt distribution from the station, thereby fully loading the station at this voltage within a few years. If the 110,000-volt stations were correctly located at three-mile centers, supplying power to a distance of 1½ mi., then such a station could distribute power to a distance of 3½ mi.; in other words, it could cover 25 sq. mi. as against 4.5 sq. mi., allowing for the fact that underground distribution feeders follow right-angled city streets.

In Fig. 2 it will be noticed that the valley of the Don River cuts through the city from the north east. This barrier had been broken down to the east, but to the north east up to 1926 very little development had taken place. For this reason, it was found possible to extend the 220,000-volt system through this territory from the original tentative location of the station into an urban location such as would allow of the above plan.

As several sites were available of sufficient size to accommodate a 180,000-kv-a. 220,000-volt transformer station, the original tentative plan was abandoned and the investigation narrowed down to a selection of these possible locations. The following features were weighed in connection with each—(a) the distance from the center of gravity of its distributed load, allowing for the gradual trend of that center of gravity with the estimated load growth; (b) the ease with which such power could be distributed from the station; (c) the ease of connection to the existing 110,000-volt system, so that all power in excess of that required at 13,200 volts could be transmitted to other existing stations; (d) the ease of access at 220,000 volts; (e) the possibility of expansion in the transformer capacity of the station, above the immediate requirements; and (f) in view of the necessarily bulky equipment to be transported to it the accessibility of the station.

The studies were completed with the selection of the present site. It may be said that this site is nearly as close to what is rapidly becoming the retail business center of the city as the original station built in 1911 was to the then retail center. It is practically one mile from the center of gravity of its 13,200-volt distribution area, but the estimated trend of this center is towards the station.

The 220,000-volt lines enter the station on a 200-ft. wide right-of-way, special bridge type structures enabling four 220,000-volt circuits to be accommodated. The 110,000-volt connection to the existing system is

accomplished by means of a 110,000-volt d-c. line, provided with two circuits of 605,000-cir. mil. aluminum and supported on special narrow-base towers erected on the railway right-of-way, immediately adjacent to which the station is located. The 13,200-volt connections to the distributing stations of the Toronto Hydro-Electric System are all underground, the possibilities of extending to the required capacity being excellent. The site has an area of something more than 12.0 acres, and the present arrangement will allow of an installation of 360,000 kv-a. transformer capacity.

System Studies

As required for harmonic circulation and for the operation of the condensers, the preliminary design of transformers included tertiary windings of approximately 60 per cent capacity, but as it was later decided that the station would ultimately deliver all of its power to the 13,200-volt distribution system, these windings were increased to 100 per cent capacity.

This arrangement of windings,—*i. e.*, three windings, 220,000-, 110,000-, and 13,200-volt, each of full capacity—practically decided the size of the transformers to be the largest that could be transported in a built-up condition between the manufacturers' plants and the transformer station, it appearing undesirable to undertake the construction of these units in the field. Four banks of three 15,000-kv-a., single-phase, oil-insulated, water-cooled units were decided upon.

The terms of the contract permitted a certain range of voltage control at the generating station, a portion of which it was considered desirable to reserve for emergency operating conditions. The condenser capacity required to maintain satisfactory receiving-end voltage regulation, while keeping within the above limitation, was calculated as 100,000 kv-a., the transmitted power being of the order of 200,000 kw. These condensers, 25,000 kv-a. per transformer bank, operate on the respective load busses to maintain the distribution voltage within the required limits.

In the preliminary arrangement, with the 220,000-volt station stepping down only to 110,000 volts, it was assumed that the condensers could operate to maintain the 110,000-volt bus voltage for parallel operation with the existing system, the regulation on the condenser bus being then relatively unimportant. With the condensers now operating on the load bus, on which the regulation is definitely limited, it was considered desirable in order to control the exchange of wattless current between the interconnected systems to introduce under-load tap-changing on the 110,000-volt windings.

The selection of the range of voltage taps required on the windings of the transformers, together with the problem of the division of load between the three windings, was the object of considerable study. During the early years of operation of the station, the load distributed at 13,200 volts would be increasing from an estimated minimum of 40,000 kw. to full-load on the transformers, while the load transmitted to other stations at 110,000 volts, to maintain the full contract demand, would be correspondingly decreasing. Further than that, it was appreciated that the distribution of load between the two secondaries would be subject to wide daily variations due to the necessity of maintaining an average week-day load factor of approximately 87 per cent on the 220,000-volt system, in order to take delivery of the energy allowed in the contract; whereas the load-factor of the 13,200-volt demand was more nearly 65 per cent.

These studies indicated the necessity of maintaining parallel between all banks on all three windings, and for this the adopted station diagram provides, though it was found desirable to insert reactors in the 13,200-volt connections.

The transformer taps adopted were: on the 220,000-volt windings, one 5 per cent tap above and below a normal of 118,000 (204,400) volts; on the 110,000-volt windings, three 2½ per cent taps above and below a normal of 65,000 (112,600) volts; on the 13,200-volt windings, no load taps, though taps are provided for the operation of the under-load tap changers.

Calculations of short-circuit currents on the interconnected system showed that if all banks were connected in parallel, values of the order of 1,250,000 kv-a. would be reached on 13,200-volt equipment, rising to nearly 1,750,000 kv-a., if the station were developed to its ultimate capacity. It was decided to set a limit of 1,000,000 kv-a. ultimate, with feeder reactors to protect the outgoing feeders. For this reason, the "star-bus" arrangement was adopted, with 5 per cent reactors between the individual transformer and feeder groups and this bus.

Values of the order of 1,250,000 kv-a. and 1,750,000 kv-a. on the 220,000-volt equipment, and 1,250,000 and 1,600,000 kv-a. on the 110,000-volt equipment, were calculated. It was decided that the future arrangement of the 110,000-volt system would be such that the short-circuit capacity in Toronto would be limited to 1,500,000 kv-a., and breakers of this capacity were installed. With these restrictions on the lower voltages, 220,000-volt breakers of 2,500,000 kv-a. rupturing capacity, practically the lowest rating, were considered as ample, and these were adopted.

During the time the design of this system was being carried out the problem of stability was receiving considerable attention. Various methods of calculation were being advanced, though methods to determine the behavior of systems under various fault conditions had not yet been presented in detail. However, it was felt that the design of this system should promote, as far as possible, the ability of the various generating equipments to remain in synchronism during system disturbances. To this end, the highest speed of clearance obtainable in 220-kv. circuit breakers at that time was specified, and the relay system designed so that under

practically any condition the relays would operate to clear faults instantaneously.

Quick response excitation systems were installed on the generators of the Gatineau Power Company, and on the synchronous condensers at Leaside. In the former case, motor-generator exciter sets driven from service generators direct connected to the main units were used, separately excited from pilot-exciters. They were equipped with voltage regulators of the exciter rheostatic type, operated from positive-phase sequence net-works. In the latter case, direct-connected main exciters were used, separately excited from pilot exciters also direct-connected, and with quick-acting regulators and positive-phase sequence networks. The speed of the condensers being 500 rev. per min., the desired speed of excitation response was obtained with these direct-connected units.

No changes were made in the excitation system at the Commission's Queenston Generating Station, this being

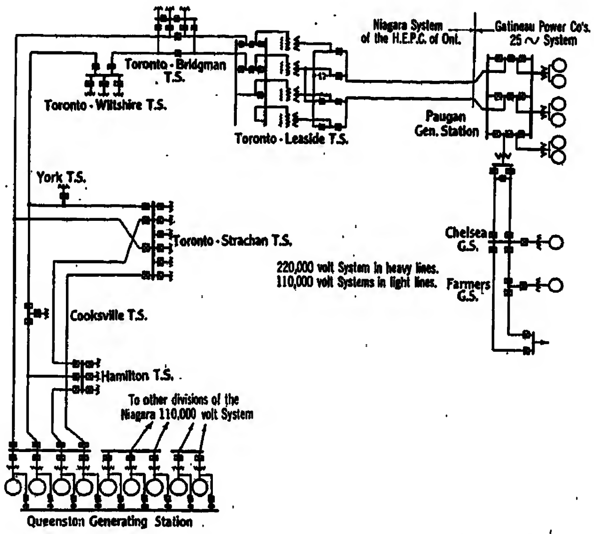

FIG. 4—DIAGRAM OF CONNECTIONS BETWEEN GATINEAU POWER COMPANY'S GENERATING STATIONS AND COMMISSION'S QUEENSTON GENERATING STATION

direct-connected exciters running at 187.5 rev per min., with standard vibrating type voltage regulators.

Operation of the interconnection (Fig. 4) required the provision of facilities for synchronizing, (or re-synchronizing in event of the systems splitting apart), sectionalizing to allow of necessary maintenance work, as well as the establishment of a routine of operating procedure.

The provision of facilities for synchronizing depends upon whether it is decided to adopt a rigid tie between systems, or whether, in event of serious trouble on either, the systems shall be allowed to part. This decision has not yet been made, as up to the present there has been only one 220,000-volt circuit in operation.

Should the 220-kv. supply be interrupted at the Leaside Transformer Station, synchronizing may be accomplished across the 110-kv. circuit breakers. Gatineau potential is obtained from the 13.2-kv. windings of the transformers, and Niagara potential is brought from the Bridgman Transformer Station, three miles distant.

For troubles not cleared rapidly on the 110,000-volt system, the systems operate at present as with a loose tie, splitting apart usually at the Bridgman Transformer Station. This is very close to the preferred arrangement, as it leaves both systems approximately self-supporting. To provide for this contingency, synchronizing facilities are also provided at this point.

To promote system stability and allow for transmission line maintenance work an automatic interswitching station about the midpoint of the line was originally contemplated. Construction of this station, however, has been deferred and will be considered after two-circuit operation and tests have determined its necessity. In the meantime to facilitate maintenance the installation of disconnecting switches at this midpoint is now being undertaken.

Dispatching on the Niagara System has in the past been divided between the dispatching of load at the generating stations on the Niagara River, centered at Niagara Falls, and the dispatching for the remainder of the system, centered at the Dundas Transformer Station. Separate control of generation has been necessary to obtain the most efficient use of the allowable water diversion at Niagara Falls, involving the optimum energy output among generating plants varying in efficiency from 30 hp. per cu. ft. per sec. to 10 hp. per cu. ft. sec.

Upon the establishment of the interconnection, the metropolitan area of Toronto, including the respective infeeds, was set up as a separate subsystem. Control of this subsystem, in so far as line and voltage conditions are concerned, was transferred to the operators at the Leaside Transformer Station.

As the problem of obtaining the full benefits of the contract amount of power and energy is so closely connected with the problem of generation in the Commission's plants, control of the power demand from the Gatineau Power Company remains with the load supervisors at Niagara Falls, who under normal conditions instruct the Leaside operators.

Between Leaside and Niagara Falls direct telephone communication is available over private wires of the Commission. Between Leaside and the Gatineau Power Company direct communication by teletypewriter and by private-wire telephone is available.

FEATURES OF THE TORONTO-LEASIDE 220,000-VOLT TRANSFORMER STATION

The general system and economic studies described had located the transformer station in Toronto, and had dictated certain of the major features to be incorporated in the actual station design.

The station site had been purchased, and studies were first made with the object of determining the trans-

former capacity that could ultimately be accommodated. These studies also included variations of the station diagram. The general requirements of the ultimate arrangement sought were, (a) that the maximum capacity of the site should be realized, keeping in view that the diagram and layout should allow of progressive additions to the station, with the minimum of revision to then existing equipment; (b) that the minimum of 220,000-volt switching be specified, on account of its expensive nature; (c) that the 110,000-volt switching arrangement should allow of future segregation, on account of short-circuit duties; and (d) that the 13,200-volt arrangement should be a unit for each bank, with reactor connections to a "star" bus, also on account of short-circuit duties.

The ultimate station arrangement decided upon is shown in Fig. 5. Eight banks of transformers, or a total of 360,000 kv-a., are provided for, with four 220,000-volt lines. For the 220,000-volt switching, a "ring" diagram has been decided upon, this being the most economical arrangement; for the 110,000-volt switching, a simplified double-bus arrangement has been adopted which will be operated as a "ring" during the early years; for the 13,200-volt switching, individual "rings" are used for each bank, the transformer connection, the feeders, the condenser connection, and a connection to the reactor bus being the units around the ring.

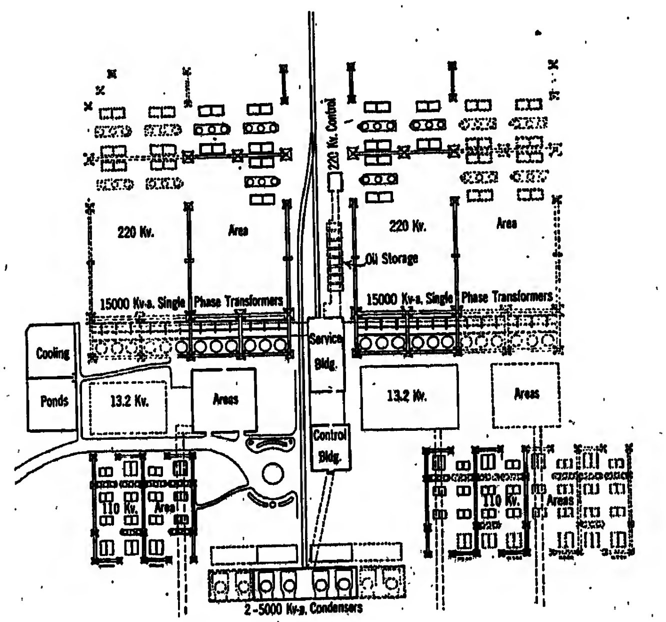

Fig. 5—Proposed Ultimate Arrangement Toronto-Leaside Transformer Station

The portion shown in heavy lines in Fig. 5 is the initial installation required for the Gatineau contract power; this installation will be completed by the fall of the present year. The station diagram for this initial installation is shown in Fig. 6.

The advantages of the "ring" diagram may be seen from a study of the 220,000-volt switching. There are six equipments to be provided for—two lines and four transformer banks—and only six 220,000-volt oil circuit breakers, yet each equipment is protected by two breakers. The ring is normally operated with all switches closed, but any breaker may be taken out for emergency maintenance, or "exercising," without any attendant rearrangement switching, and without greatly endangering the security of the station. Further, there are no extensive bus sections, a failure on which might result in a major interruption. The diagram may not of course be too greatly expanded, as an excess of units in the ring tends to weaken the arrangement. It is considered that six units is near the maximum, and for the extension to the station, a second ring will be used, probably with a single or double tie between rings.

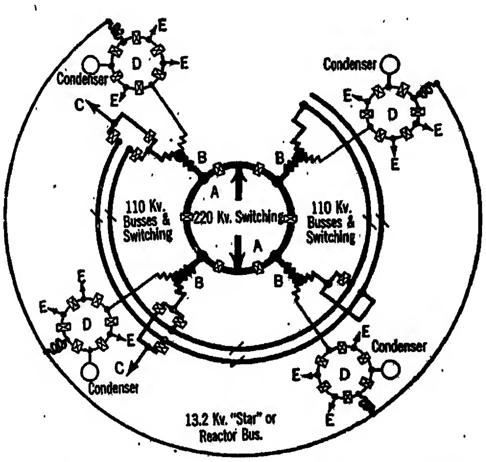

Fig. 6—Schematic Circle Diagram—Main Switching. Toronto-Leaside Transformer Station

A. 220-Kv. incoming lines
B. Three-winding transformers 220/110/13.2 kv.—45,000 kv-a. each winding
C. 110-Kv. outgoing feeders
D. 13.2-Kv. ring bus
E. 13.2-Kv. outgoing feeders

Because it is desirable to operate the ring normally closed, motor-operated, isolating disconnecting switches are installed on each piece of equipment, so that if any equipment is to be removed from service for some time, its isolating switch may be opened and the ring again re-established.

220,000-Volt Switching

The 220,000-volt area is entirely outdoors, typical fabricated steel structures being used. (Fig. 7.) A minimum clearance of 12 ft. between phase wires has been specified, although clearances up to 20 ft. between relatively long strain-equipped leads are provided. Minimum ground clearance has been specified at 7 ft. 6 in. Both these figures are based on grading rings being provided; as these rings have not yet been installed, actual clearances are somewhat higher.

The oil circuit breakers have a current rating of 800 amperes, and a rated rupturing capacity of 2,500,000 kv-a. They are equipped with oil-filled bushings rated as being suitable for operation at 127 kv. to

ground; *i. e.*, 220-kv. solidly grounded, or 187-kv. isolated, neutral system, although provision has been made for bushings of a size suitable for a 220-kv. isolated neutral system.

Low-freezing oil is used in these breakers, although two 1000-watt immersion heaters have also been installed in each tank to prevent the oil from thickening at below zero temperatures. Also, in the mechanism housing, the breaker operating mechanism being of the centrifugal type, a 500-watt heater has been installed to eliminate dampness as well as to prevent slowing up of the operations of the mechanism due to thickening of the lubricant.

All the 220-kv. disconnecting switches are upright, mounted on pillar insulators, each with three stacks of six 17½-in. by 14½-in. three-skirt units. They are of the high-pressure contact type, rated at 1000 amperes, and are all motor operated.

When used as isolating switches on an oil breaker, the two sets of switches operate together from one control,

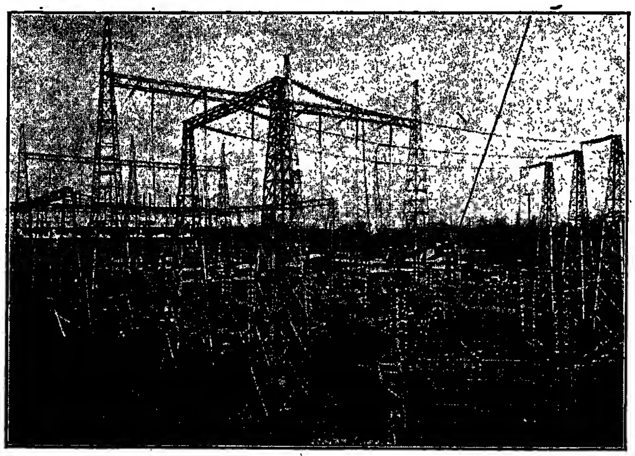

Fig. 7—220,000-Volt Switching for First Unit, Toronto-Leaside Transformer Station

electrical interlocks being provided to prevent their being operated under load. On the line disconnecting switches, hand-operated ground switches have been provided on the line side, means also being provided for single-pole operation when required for testing. Non-corrosive bolts are used on all bolted connections exposed to the weather which are likely to require to be unbolted in case of replacements.

The 220-kv. leads are constructed at three elevations. The lowest conductors are 20 ft. above ground and are of 2-in. copper tubing, supported on post insulators, with a maximum spacing of 24 ft. between supports. Provision is made for contraction and expansion of this tubing. The upper two tiers are spaced so as to give 20 ft. minimum clearance between tiers. They are both suspension-equipped—twenty 5-in. standard units, strained from the steel structures and designed for a maximum pull of 3000 lb. with ¾-in. ice loading and 8-lb. wind. Hollow-conductor copper cable with I-section core is used for these leads, having a conductivity equivalent to 750,000-cir. mil copper and an outside diameter of 1.26 in., sufficient to prevent corona formation in all weathers. In clamping this cable, it was found necessary, in order not to crush it, to use clamps which would exert a uniform pressure around the circumference of the cable. As few joints as possible are made, and no soldered connections are used at all.

110,000-Volt Switching

Similar construction is used for the 110-kv. switching, namely, outdoor equipment with copper tube busses supported on post insulators, and strain copper cable busses with suspension insulators. Post insulators have two units, each 20 in. high with four skirts, and the strain positions have 10 suspension units. The oil circuit breakers are rated at 135 kv. 600 amperes, with a rupturing capacity of 1,500,000 kv-a. and condenser bushings and solenoid operated mechanisms. Electric heaters are provided for heating the oil and mechanism housings of the breakers. Similar to the 220-kv. section, all connections on busses and to the equipment are clamped.

The disconnecting switches are of the swivel type, with three stacks of insulators, the center one rotating. The contacts are of the finger type. The isolating switches on the breakers are hand operated, but the transformer and line disconnecting switches are motor operated. The line and transformer switches are equipped with hand gang operated ground switches.

13,200-Volt Switching

The delta on the 13,200-volt connections from the transformer banks is formed on an outdoor steel structure immediately behind the transformers. For the first two banks of transformers, the three-phase bus is then run into a building which houses the complete 13-kv. switching equipment for these banks. All equipment in this building is for indoor use, and is a duplicate of that used in the Commission's Queenston Generating Station.

The oil breakers are housed in compartments with the bus connection to them carried through wall bushings mounted on the wall of the compartment. All disconnecting switches are gang operated, the isolating switches on the circuit breakers being hand operated and the feeder and transformer switches being motor operated by remote control from the control room. These disconnecting switches, as well as reactors and potential transformers, are also housed in separate compartments. The operating wheels for the hand operated switches are located outside the disconnecting switch-rooms in the passages. The busses, which consist of ¼ in. by 4 in. copper bar laid on the flat, are supported on extra heavy duty bus insulators.

The switching for the second two banks is radically different. From the delta bus, cable is run to separate

phase structures. The equipment is of outdoor isolated-phase metal-clad type.[1]

The breakers are solenoid operated with an electrical interlock only. The breaker-isolating disconnecting switches are formed by the raising and lowering of the breaker oil tanks and mechanism by motor operation, the breaker bushing being equipped with a contact

FIG. 8—INSTALLATION OF FIRST TWO 45,000-KV-A., 220,000-VOLT BANKS OF TRANSFORMERS

Tap-changing equipment immediately to the rear of transformers, and not visible in photograph. Toronto-Leaside Transformer Station

while the bushings connecting through to the bus are equipped with floating fingers. An automatic shutter closes the opening when the breaker is lowered. The feeder disconnecting switches are oil immersed and motor operated.

The complete equipment for each phase is housed in a steel covering, the bus being located in a compound-filled compartment just under its roof.

MAIN TRANSFORMERS

Four banks of transformers, and one spare, have been installed, each bank consisting of three 15,000-kv-a., single-phase 25-cycle, 118,000/65,000/13,200-volt oil-insulated water-cooled three-winding outdoor transformers. (Fig. 8) The banks are connected in star on the high-voltage winding, with the neutral point solidly grounded. The intermediate voltage windings are connected in star,—at present with the neutral isolated, the system neutral however being grounded through a resistance at the Queenston Generating Station. This intermediate voltage winding is provided with full insulation. The low-voltage winding is connected in delta and grounded through a zigzag reactor.

Each of the three windings has a continuous rating of 15,000 kv-a. A hand wheel is provided on top of each transformer cover for operating the tap changer on the high-voltage winding, when the transformer is not energized. Tap-changing equipment for operation under load is used on the intermediate voltage, with a special series transformer to boost or buck the terminal voltage 7½ per cent in 2½ per cent steps. This special transformer is energized from the low-voltage winding of the main transformer. The tap changers may be operated by hand on each transformer, or three, comprising a bank, may be operated simultaneously by remote control from the control room. The transformers are shell type and the outlet bushings are condenser type.

The tanks are made in three sections, which, with the cover, were shipped to the station unassembled. The main core was completely assembled in the factory, as were the series and preventive transformers; then each one was shipped in oil in special shipping tanks. Complete assembly of the transformer was made in the service building.

SYNCHRONOUS CONDENSERS

In the synchronous condenser installation at Leaside, a radical departure from standard designs has been made in that vertical-shaft outdoor units have been adopted. (Fig. 9.) They have a combined spherical thrust and guide bearing located below the rotor, with direct-connected main and pilot exciters located below the thrust bearing. There are four such units, each

FIG. 9—INSTALLATION OF FIRST TWO 25,000-KV-A., 500-REV. PER MIN. VERTICAL-SHAFT SYNCHRONOUS CONDENSERS. TORONTO-LEASIDE TRANSFORMER STATION

rated at 25,000 kv-a. 500 rev. per min.; one connected to each bank of transformers.[2]

From a survey of existing condenser installations and experience with large generating apparatus, it was decided that units of the size dictated by preliminary studies should be of the totally enclosed type, with some means provided for the cleaning of the cooling medium. With such a unit, little if any additional cost would make the cover weathertight, which contributed to the adoption of outdoor machines.

Comparative estimates were prepared of indoor and outdoor arrangements, with both horizontal and vertical

1. For references see Bibliography.

shaft units. These estimates pointed to an outdoor installation, with a slight advantage in favor of the vertical shaft unit. The vertical shaft arrangement was finally selected, it being decided that such units were relatively more accessible for maintenance work.

Preliminary designs were worked out in cooperation with the engineers of the manufacturers, with the object of arriving at an arrangement which would best lend itself to ease of maintenance, and require the smallest amount of exposure to weather during dismantling. The arrangement decided upon is shown in detail in Fig. 10. The combined thrust and guide bearing is

The main unit is located above the ground level and is completely surrounded by a ventilating housing, the roof of which is lagged to prevent condensation. Automatic dampers control the air circulation, the object being to minimize coil creepage by maintaining constant machine temperature. All air drawn from outside is screened before entering the housing.

For floating the rotor during starting each unit is equipped with a high-pressure oil pump. The lubricating system is of the unit type provided with duplicate motor-driven lubricating pumps to circulate the oil through a tubular water cooler to the thrust and upper guide bearing. A central air compressor is

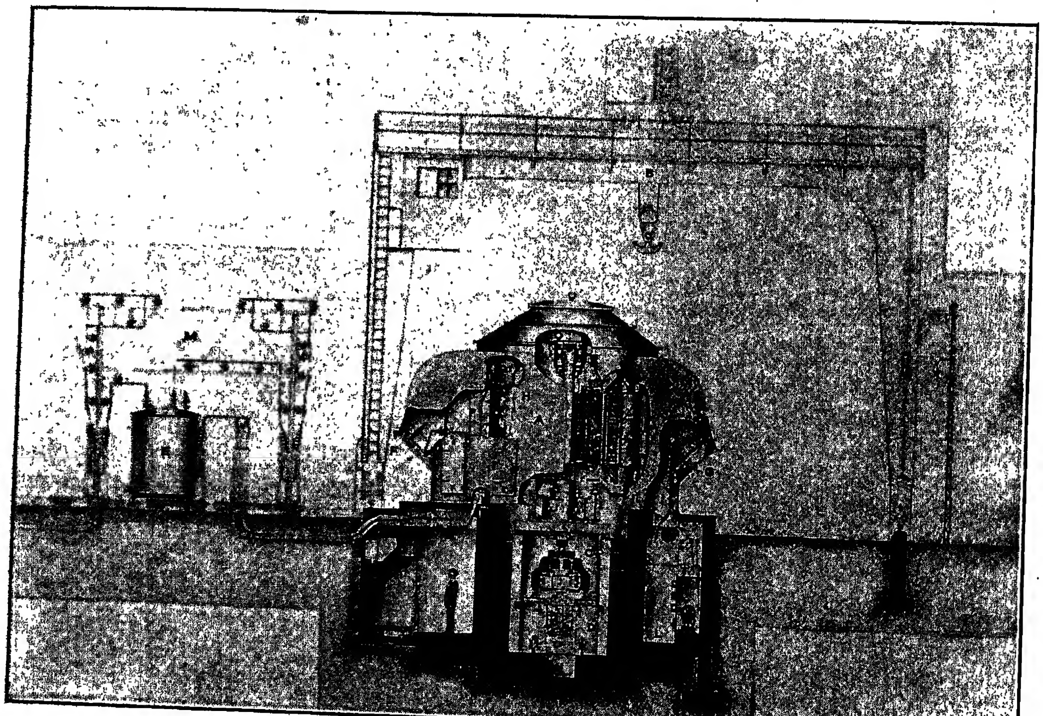

FIG. 10—25,000-KV-A. SYNCHRONOUS CONDENSER. TORONTO-LEASIDE TRANSFORMER STATION

A 25,000 Kv-a. condenser, 500-rev. per min., three-phase, 25-cycle, 13,200 volts
B 80-Ton gantry crane
C 150-Kw., 125-volt main exciter
D 30-Kw., 250-volt pilot exciter
E 9000 Kv-a. auto transformer
F Main incoming air damper
G Main outgoing air damper
H Recirculating air damper
I Damper for basement heating
J Spherical seat thrust bearing
K Upper guide bearing
L High-pressure oil pump for starting
M Starting structure and equipment
N Truck for handling exciters
O Threaded hole for rotor lifting eye
P Air filters
Q Current transformers

seen below the rotor, with the exciters (main and pilot) below this bearing. All moving electrical connections, therefore, are located indoors within the foundation, under the view of the operator and readily accessible.

To dismantle the machine, the exciters are disconnected immediately below the bearing, and are moved from under the machine on a small truck provided for the purpose. Removal of a small cover allows the crane (80-ton capacity gantry) to take the weight of the rotor, certain blocking is removed, and the rotor with its bearing is dropped down into the foundation. Replacing the cover, the unit is again weathertight and the armature and field windings are completely accessible.

provided for braking purposes, the speed of the unit being first reduced to one-half by dynamic braking. Both starting and stopping operations are fully automatic with remote control.

A central carbon-dioxide fire protection is provided, augmented by two copper water-rings near the armature end-connections.

In order to minimize vibration, care has been taken to isolate the machine foundations from adjacent structures. This is accomplished by using cork between the foundation and the roof of the condenser basement, and mastic between the base of the foundation and the basement floor. The soil on which the

foundation is located being of hard blue clay bordering on shale has not been disturbed.

Lightning Protection

The problem of providing what would appear to be adequate lightning protection for the 220,000-volt station was given considerable study. When applied on 220,000-volt systems, the protective value of the available types of lightning arresters was very indefinite. The decision was made to initially omit arresters, but to coordinate as well as possible the transmission line and station insulation, at the same time using an increased number of ground wires on the adjacent portion of the line.[3]

For a distance of some two miles from the station, the number of suspension units (5-in. spacing) was reduced from 18 to 14, four ground wires were used instead of two, and the height of the supporting structures reduced some 13 ft. The increase in number of ground wires was expected to decrease the surge impedance of the phase wires, and therefore to cause a lowering of the voltage of surges entering this section.

The suspended bus in the station was protected by three ground wires, the height and separation of these ground wires being such that the bus would be protected from direct hits.

In the interval, the characteristics and protective value of arresters have been more clearly defined by extensive field and laboratory investigations, and a special design of 220,000-volt valve type arrester is now being installed. This special design has been chosen to protect the arrester against rise of dynamic voltage upon loss of load, at the same time affording maximum protection to the station apparatus.

Normally 18 units are in service, with four further units short-circuited by a disconnecting switch. This disconnecting switch, normally closed, is opened automatically by an over-voltage relay if the dynamic voltage exceeds a predetermined value. These arresters are being installed immediately adjacent to the transformers, one on each bank.

Relaying

Of necessity the relay protective equipment at Leaside Station includes not only that required for the actual station protection, but also that required for the protection of the transmission system. This is more particularly true with the "ring" arrangement, as certain of the oil circuit-breakers have dual functions, being both line and transformer breakers at the same time. For these reasons, the combined relay scheme will be described here.[4]

The relay protection for this system is designed to meet, so far as possible, the following requirements: (a) the clearing of faults, instantly and selectively, leaving sound portions of the system in service; (b) in case of failure to clear instantaneously, to provide stand-by effect to separate the system into main sections and then to clear the section on which the fault persists; (c) to be fully effective (without readjustment) to both instantaneous and stand-by features, over a wide range of connected generator capacity including the condition where the fault current may be less than normal full-load value; (d) to be, in itself, safeguarded against tripping from accidental causes when no system fault exists; to be capable of easy checking, calibration, and testing; and to give as many data as possible as to the nature and location of the fault; and (e) to be capable of incorporation, without important changes, into a developing system, as well as capable of extension into existing systems.

Relaying which practically meets these requirements has been applied to the 220,000-volt lines, the Leaside Transformer Station, and is being extended to the lines and stations of the Gatineau-Niagara interconnection.

For relay purposes, the system may be considered as divided into elements, each bounded by automatic oil circuit breakers. These breakers carry the relaying current transformers, bushing type, and each such breaker is included within the respective element; *i. e.*, these "boundary" breakers are bracketted by two elements. The elements, in turn, are of two classes: those entirely within the station, (transformer banks and their wiring or bus-sections, known as "Zones"), and those which extend away from the station, (lines and feeders).

Each station zone is covered by simple current differential instantaneous protection, set below normal load current. To the condensers are added split-phase features on the stator windings.

To take care of incipient faults, and avoid tripping on magnetizing current when energizing, the transformer banks have an inverse time feature. The external wiring of the transformer zone is covered by instantaneous differential protection.

At each end where there is power infeed, long lines and feeders, at all voltages, are equipped with directional double-distance-range impedance relays, for phase-to-phase, and phase-to-ground faults. One set of distance relays with range definitely short of the remote end of the line, clears instantly for faults within 70 to 80 per cent of its end of the line. The second set, with range definitely beyond the remote end of the line, is timed under all conditions at about 0.6 sec., to be selective with faults on the bus and other lines.

The relays used consist of two solenoids on opposite ends of a balance arm, one actuated by phase-to-phase, or phase-to-ground, voltage and the other, by phase or residual current. The potential coil holds the contacts apart; the current coil tends to close them. The relay may be set for a ratio, volts divided by amperes, which allows the contacts to close instantly, and which, when applied to a line, corresponds to a length of the line. Any timing is obtained by a definite time auxiliary relay.

Other relays include directional, plunger type current, voltage, and auxiliary tripping relays of necessary

ranges, having very low energy consumption for use on 25-cycle bushing current transformers.

The distance relay is usually set well below full-load current, so that if it loses potential it will operate during normal operation. To avoid this, where relays are so set, a duplicate of the long range distance relay is used, energized from a duplicate source of potential.

For stand-by protection on phase faults, a set of distance relays of long range, usually duplicated as to potential because current settings are low, and timed beyond the instantaneous features—usually 1.2 to 1.4 sec.—are applied on each transformer bank. For grounds, residual current, or voltage, relays are used, timed in the same way.

For 220-kv. potentials, 13,200-volt potential transformers have been used on each bank, with transformer drop compensators to simulate the 220-kv. voltages. For use with line relays, these are selected by a switching arrangement of potentials.

The short 110,000-volt connection to the existing system is protected by current-differential pilot wire.

Grounding

The attempt has been made at Leaside to establish one "ground" plane for the whole site, and thus avoid ground gradients due to fault currents in any one section of the station. Copperweld rods have been driven at the bottom of the transformer tunnel, cooling pond, and in all tower footings, and these are connected together with 2/0 copper wire. The 2/0 copper wire has also been laid along all building foundation footings just below the weeping tile, in all cases carefully covered with a few inches of earth to increase its contact area.

The site has been divided into various areas and the various ground networks segregated on a ground test-bus in the transformer tunnels. The combined network has resulted in a ground resistance of less than one-tenth of an ohm, which so far has remained consistently low.

The ground wire shielding over the 220-kv. line has been extended across the station at a height of 15 ft. above the highest bus, and is tied directly to that section of the general ground bus to which the 220-kv. transformer neutrals are connected. This shielding is extended across the 110-kv. switching area, and thence to the ground wire on the 110,000-volt line connection to the Niagara System.

Batteries and Charging

Two storage batteries, one 250-volt and the other 48-volt, are installed to furnish a reliable source of power for the control of the station equipment, emergency lighting, and signals.

Duplicate charging sets are provided, each consisting of a three-unit motor-generator set, 550-volt, three-phase motor, and two diverter-pole d-c. generators,—one for 250-volt and the other for 48-volt, mounted on either end of the motor shaft. They are operated "floating" and have given very excellent service.

Lighting

Power for lighting is obtained from two banks of three 50-kv-a. single-phase 550-volt and 199/115-volt delta-star dry type transformers. Emergency d-c. lighting is provided in the control building, and upon failure of the a-c. supply is automatically placed in service. Holoplane refractors have been used throughout, and in the wiring of all the outdoor standards, single-conductor lead-covered cable, with the lead forming the return circuit, has been used.

Oil Handling System

Permanent oil piping is extended from a central oil-handling room to near each oil-circuit breaker and transformer, from which point, flexible hose connections are made as required. When removing oil from any equipment, it is pumped into any or all of six oil storage tanks having a total capacity of 30,000 gal. Two 40-gallon blotter type filters are used to treat the oil when replacing it. A by-pass has also been provided at the equipment, permitting the good oil piping to be flushed out before using.

Water Supply

Two cooling ponds of reinforced concrete construction and having a total capacity of 225,000 gal. have been built immediately adjoining one another. They are equipped with spray nozzles and enclosed with wooden louvers.

Cooling water for the transformers and condenser bearings is circulated by means of two centrifugal pumps, each with a capacity of 1000 gallons per min. at 100 ft. head.

Water for domestic purposes, and for the cooling-pond make-up, is purchased from the town of Leaside.

Communication

At Leaside, communication is provided with the load-dispatcher of the Gatineau Power Company at Val Tetreau, with the Commission's load-supervisor at Niagara Falls, and with other necessary stations on the 110,000-volt system and on the Toronto Hydro-Electric System.

Teletypewriter service over circuits of the Bell Telephone Company is used for practically all communication with the Gatineau Power Company. This service was chosen after consideration of carrier-current telephone, long and short wave radio, and direct private wire telephone over circuits constructed on the 220,000-volt right-of-way. To date the service has given excellent satisfaction, the printed message being a desirable feature.

The telephone circuit on the 220,000-volt right-of-way was first constructed through the inaccessible country in the east, but its performance was so good that it has since been extended to Leaside. Direct telephone service is now available to the Paugan Generating Station, but the service is used principally for com-

munication with patrol points and for load dispatching only in emergency.

Other communication is over the Commission's private wire system, or Bell telephone circuits within the city.

Within the confines of Leaside Station, and also to the head office of the Commission, communication is provided by means of a private automatic telephone exchange. Fixed instruments are installed in a number of convenient places, and jacks for portable phone connection are provided in many others.

Control

Because of the complications introduced by the three-winding transformers, it was considered desirable, if not essential, to provide an arrangement of control which would lend itself to the incorporation of a dummy bus scheme. It was estimated that approximately 200

Fig. 11—Control Desk for First Unit—Toronto-Leaside Transformer Station

Four such desks will be required for ultimate station capacity

controllers would be needed for the ultimate station, and in order to confine these controllers within a reasonable space, miniature control has been adopted.

Standard telephone keys mounted on the top of desks about the size of ordinary office desks have been adopted. One of these desks is shown in Fig. 11, there being four required for the ultimate station. On the desk shown are assembled all the controllers and signal lamps required for:

One—220,000-volt line
Two—three-winding 45,000-kv-a. transformer banks
Two—110,000-volt lines
Six—13,200-volt feeders
Two—25,000-kv-a. condensers
Two—connections to the paralleling bus

Standard telephone equipment operated at 48 volts, has been used throughout, and use has also been made of the double-pole telephone key to isolate the operating coil circuits of the interposing relays when they are not in use. To facilitate tracing of circuits, color code is carried through the wiring, and terminal strips are located at all points where multiple-conductor cables end.

Individual keys are protected against accidental operation by a master key in the front of each desk, to be operated simultaneously. Interlocks have been provided on the 250-volt portion of the control to prevent operation of the disconnecting switches unless the oil circuit breakers in conjunction with them are open.

Features of the 220,000-Volt Transmission System

In undertaking the construction of 220,000-volt transmission lines from the interprovincial boundary between the provinces of Ontario and Quebec to Toronto, it was early recognized that the problems that would arise would be many and varied. The Commission had not previously constructed any lines operating above 110,000 volts, nominal; nor were there any lines in Canada; and but few in the United States, operating at that time at 220,000 volts. The lines that were then in operation were located in territories much less subject to atmospheric disturbances than the territory through which these lines were to be constructed. As evidence of this fact, it was stated at that time that 220,000-volt circuits would seldom be involved in more than single-phase-to-ground flashovers due to lightning, whereas two flashovers involving more than one conductor have already been experienced. For at least one-half the distance, these lines were to be built through extremely rough country, accessible only over the poorest of roads, and generally only superficially surveyed.

Route

The question of the route to be followed by these lines was very fully investigated, the alternatives considered lying between the shortest and most direct route, which involved more than 100 miles through the type of country described, (in places 25 miles from the nearest railway) and a route diverted well to the south, to take advantage of the well-developed country paralleling the shore of Lake Ontario. Economic considerations outweighed any advantage of the latter route, and the generally direct route has been followed (Fig. 12).

It was considered desirable to have these lines pass close to a future power development known as Chats Falls, on the Ottawa River, and this governed the choice of location of the river crossing. The route is therefore not direct from the generating source, but as nearly as possible direct from this latter point.

Survey

Where absolutely dependable maps are available, a large proportion of the work of locating a line may be done in the office before any ground work is undertaken. For the majority of the territory to be traversed in this case, there were no such maps available, and it was

realized that to survey a route by means of field survey parties would be a long and tedious task. As the question of time was very important, (it being known that the first circuit would have to be completed within two years), the newer art of survey by aero-photography was adopted.[5]

This work was carried out by a commercial organization under contract, the company supplying the Commission, two sets of oblique photographs—(looking respectively north and south over the preliminary center-line), one set of vertical photographs looking down on the finally selected center line, and one complete mosaic for the whole line.

Easements were taken for a 40 year period, covering the right to erect and maintain towers and including the overhanging and stringing rights. Wherever clearing was necessary, these rights were purchased in addition, the farmer usually also being given the contract to carry out the clearing. Incidental damage to trees, crops, fences, etc., due to construction work, was settled for later.

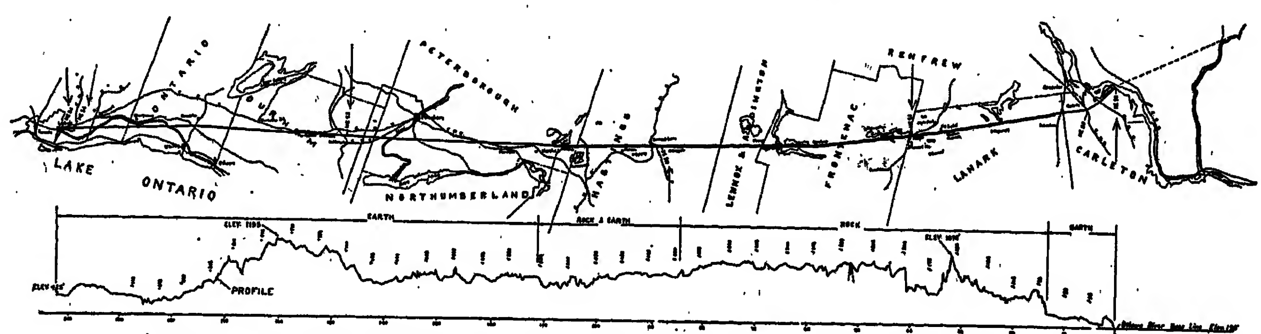

Fig. 12—Plan and Profile of H. E. P. C. (Gatineau) 220,000- Volt Transmission System

These photographs were made as follows: On the best maps available a preliminary route was drawn. The oblique photographs were taken flying over this route, and from the information thereby made available, the maps were corrected and all obstacles shown. The final route was then selected, and the vertical photographs taken flying over the new center line. As is customary, these verticals were taken with a 60 per cent overlap for the making of the most accurate mosaics and use with a stereoscope to show the contours.

On the mosaics, with the aid of the information available by the use of the individual prints under the stereoscope, the individual tower sites were located. The importance of the use of the stereoscope in this way can hardly be overestimated, as even the minor contours are revealed in remarkable detail. Field survey parties were then only required to run the center line as shown on the mosaic, stake the tower locations, and mark the limits of the right-of-way for clearing purposes.

Right-of-Way

The adoption of aerial surveying was found to be of considerable assistance when securing the rights for right-of-way. The easement method has been used throughout with the exception of a short section close to Toronto. The right-of-way agents were supplied with copies of the mosaic showing tower locations, and as the farmers along the route had not been disturbed by field survey parties working ahead of the agents, the first intimation that a number of them received of the lines crossing their property was the appearance of the agent to arrange for easements.

In the case of crossing Crown lands, only notice of occupation given to the Government was necessary. On these lands, clearing was done by the Commission's Construction Department. In all clearing, provision was made for haulage of material to the tower locations, by cutting a strip 12 ft. wide to the ground level.

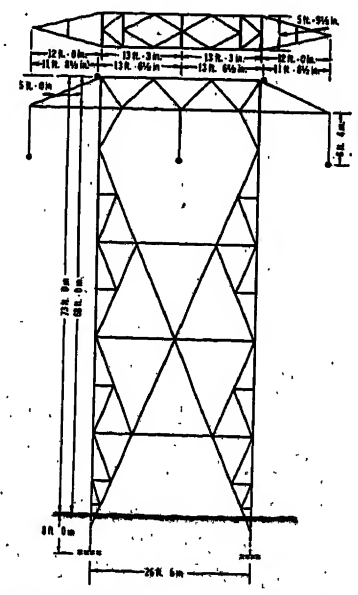

Fig. 13—Outline Standard Single-Circuit Suspension Tower

The section in which the lines are located on purchased right-of-way extends for about 10 mi. east of Toronto. The purchased strip is 450 ft. wide, this being considered necessary to provide an adequate entrance for four 220,000-volt single-circuit tower lines, which will ultimately run into this station.

Design of Towers

Before undertaking the design of structures, several lines already operating at 220,000 volts were inspected

and studied. Acknowledgment is made here of the courtesies extended the Commission's representatives at this time, all visited organizations willingly passing on to the Commission the benefit of their operating experience. Particular attention was paid to the question of tower clearances, it being considered

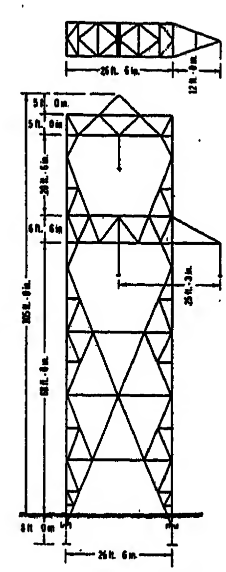

FIG. 14—OUTLINE STANDARD SINGLE CIRCUIT TRANSPOSITION TOWER

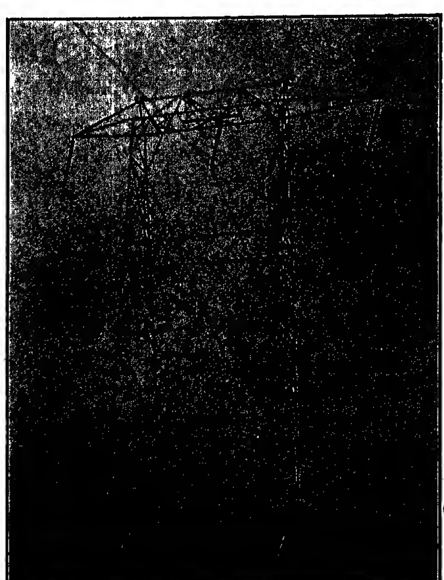

FIG. 15—ILLUSTRATING USE OF LIGHT ANGLE TOWER WITH TEN FT. EXTENSION

Note extension of outside arm and provision for off-set of center conductor

desirable to be even more liberal in this respect than on any line at that time designed.

The standard suspension tower adopted is shown in Fig. 13. Conductor spacing is 25 ft. 3 in., which, with a 100-in. insulator string, insures a minimum clearance of 6 ft. to the tower steel assuming a maximum swing of 45 deg. Two ground wires are provided, located 14 ft. above and 12 ft. inside the outside power conductors, the minimum clearances at rest being 25 ft.

Towers are designed for a maximum conductor tension of 10,000 lb., and for a maximum ice and wind loading of ½-in. ice, 8-lb. wind, 30 deg. fahr., along the line, and ¾-in. ice, 11-lb. wind, 30 deg. fahr. across the line. Towers are constructed of carbon steel with silicon steel legs, the standard suspension tower, including footing, weighing some 10,400 lb.

In addition to the suspension tower, a light-angle tower, and what is known as a semi-anchor tower are provided. The outlines are approximately the same as for the suspension tower, the weights being 11,000 lb., and 15,900 lb., respectively. The light-angle tower is designed for long spans and for taking angles up to 4 deg.; the semi-anchor tower provides for dead-ending of conductors and for taking angles up to 20 deg. Both

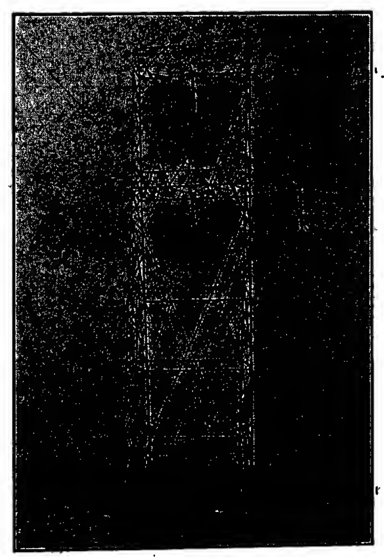

FIG. 16—TYPICAL INSTALLATION OF TRANSPOSITION TOWERS—SAME TOWER USED RIGHT AND LEFT-HAND

these towers are provided with special off set heads for angles. In order to maintain the specified clearances, the arm on the outside of the angle is made longer, and by means of a drilled plate, provision is made to move the point of support of the center conductor to maintain its position in the center of the tower.

The standard transposition tower is shown in Fig. 14. Transpositions are of the rolling type, involving two towers of the type shown,—one right-hand and one left-hand. There are 33 transpositions per line in the 203 mi., which has been found sufficient to result in excellent service over the closely paralleling telephone circuit.

Ten-, twenty-, and thirty-foot extensions are provided for all towers, all of part silicon construction.

FOOTINGS

All footings in earth are of the grillage type, consisting of channel sections with cross-ties. Footings vary in

weight from 1850 lb. for the suspension tower to 2360 lb. for the semi-anchor. They also vary as to the depth to which they are buried; for suspension and transposition towers, they are buried to a depth of 8 ft., for light-angles 8 ft. 6 in., and for semi-anchors, 9 ft. 6 in.

The stub-angle to which the tower leg is bolted is provided with a series of bolt-holes at 3-in. centers, making an adjustable telescopic joint by means of which minor variations in ground level at the four footings may be taken care of.

Rock footings consist of two channel members as in the case of the earth grillage, but without the cross ties. Each leg is anchored to the rock by means of two rock bolts fashioned in such a way that, when driven, a wedge expands the bottom of the bolt. The whole footing is then grouted in.

Span

The standard span adopted for these lines is 1056 ft. Actual spans vary up to 2263 ft.; this being the only span, however, in excess of 2000 ft. There are approximately 1000 towers per line, or an average slightly under five to the mile.

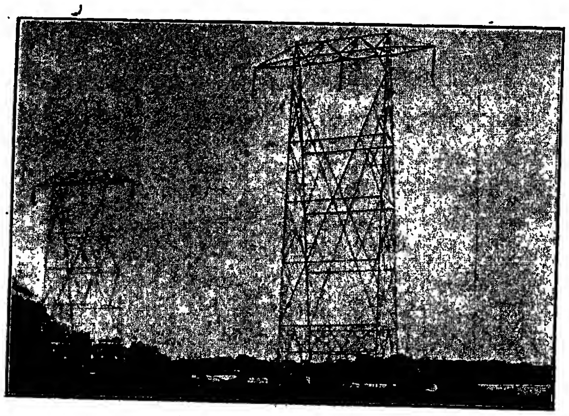

Fig. 17—General View Two Circuits Crossing Otonabee River.

900 ft. span—20 ft. extensions on near towers to provide 60 ft. clearance to water level

A special attempt was made on these circuits to reduce the number of insulation points to a minimum. On the first circuit there are only 16 dead-end positions, —three at angles in excess of 18 deg., six at proposed interswitching points, four at long spans, two at railway crossings, and one at the terminal. At railway crossings, where it was formerly the practise to dead-end on each side of the crossing, two points of insulation are used on each side of the crossing, but all insulator strings are maintained in the suspension position, the crossing span usually being somewhat shorter than standard.

Tower extensions also have been used freely to lengthen a span—for example, across a minor depression, rather than use an intermediate tower. This has the result of somewhat increasing the average height of the conductor, but it does reduce the points of possible insulation failure. In the 203 mi. of the first circuit constructed, there is actually an average of only 1054 insulation points per conductor.

Insulation

The subject of insulation for transmission lines of the various higher voltages has been, and still is, the subject of extensive field and laboratory investigations. These investigations have pointed to the desirability of some fourteen to sixteen 5-in. spacing suspension units for 220,000-volt lines. For the distribution of the electrostatic stresses some investigators have stressed the advisability of the installation of grading rings or similar provision, while others have doubted the efficacy of such devices.

Considerable attention has been paid to this point. The facilities of the Commission's laboratories do not permit of tests in this regard, but with the cooperation of the manufacturers investigations have been carried out. As a result it was decided to install eighteen 5-in. spacing units in all suspension positions, without grading rings or arcing horns. It was felt that as only 16 units could be installed if grading rings were used, in order to maintain clearances, the insurance of the additional two units was well worth while. It is hoped that with the protective scheme provided the speed of clearance of all faults will prevent damage to insulation due to cascading. So far this has been consistently true. If it is found desirable to add rings later, provision has been made in the conductor clamp for so doing.

In all strain positions, heavy-duty 5¾-in.-spacing units are installed instead of the 5-in.-spacing unit, the number of units being the same.

Conductors

The power conductors are 795,000-cir. mil steel-reinforced aluminum cable, 27.2 per cent steel. Conductor is strung for a maximum tension of 10,000 lb., at which tension the maximum sag on a standard span is 36 ft. Minimum clearance to ground is established at 24 ft., except in suburban areas, road and rail crossings, etc., where 30 ft. clearance is maintained, while radial clearance to foreign structures and trees is 20 ft., and to the telephone circuit 35 ft.

Conductor joints are of the compression type, a steel sleeve being used on the core, and a long aluminum sleeve on the outside of the conductor.

Cable clamps are of a type designed to allow three-way movement of the conductor at the point of support, in order to mitigate vibration troubles. In addition, two types of vibration absorbers are used. The one provides an additional length of conductor clamped above the power conductor in the same clamp, and extending three ft. beyond the clamp on either side where it is again fastened to the power conductor. The other provides a layer of aluminum rods about 10 ft. long, secured in the main clamp and twisted about five times out over the power conductor, the ends being secured with an auxiliary clamp. The latter method is

apparently functioning better, although it is more expensive to install and probably represents a greater hazard, as strands improperly laid or secured may get loose.

The two ground wires are of the same construction as the steel core of the power conductor, being seven 0.1214-in. strands of galvanized crucible steel cable. The same compression joint as for the steel core is therefore used, heavily coated with bituminous paint. The cables are attached to the tower by means of a clamp similar to that used on the power conductors. This type of clamp has been considered essential, in order to avoid failures of the ground wires due to crystallization.

Special Terminal Section

For approximately two miles in the vicinity of the terminal transformer station, the structures and line design have been modified to conform with the coordination of line and station insulation strength, as previously discussed. The structure height has been reduced some 13 ft., and the span has been reduced to about one-half. Four ground wires instead of two have been installed, and the number of suspension units reduced to 14. For about one mile from the station the ground wires are "conducting," composed of fifteen 0.12-in. aluminum strands and nineteen 0.096-in. steel strands. All other factors of design are unchanged.

Since the erection of the first circuit, a special "bridge-type" structure, having two tiers of conductors, has been designed for erection in the half-mile section immediately adjacent to the transformer station. At this point, real estate is expensive, and the right-of-way has been restricted to 200 ft. This "bridge structure" accommodates one 220,000-volt circuit in a width of 50 ft., or allows of four such circuits on this section of right-of-way. It is anticipated that this type of structure will be used in future in similar urban locations.

Construction

Construction of the first of these 220,000-volt circuits was commenced in July 1927 and completed and placed in operation on October 1, 1928. Construction of the second circuit was commenced in May 1929, and approximately one-half was completed by October 1929. Since that time this half-circuit has been in service, connected in parallel with the first circuit, to obtain the benefit of the additional conductivity. The whole circuit is scheduled for completion in July 1930.

As the country is well-developed relatively flat farming country, construction of the westerly half of the system presented no great difficulties. Materials were delivered from the nearest rail point over good roads, in practically all cases by local trucking concerns working under contract. This method was adopted in place of having a considerable sum invested in construction machinery, and has been found to be very satisfactory.

For the easterly half of the system, all material was delivered during the winter. At this time, the deep snow tends to improve the road conditions, and delivery costs are very much lower. Most of the heavy clearing encountered in this section was also done in the winter time.

Line erection was carried out in three stages. Footings were dug and grillages placed by footing gangs, usually from 50 to 75 men. Templets were used in setting and leveling footings, the telescopic joint between the tower legs and the stub-angles assisting greatly in this regard. In the case of rock footings, the overburden and loose rock was first stripped away, so as to provide as level a surface as possible. The

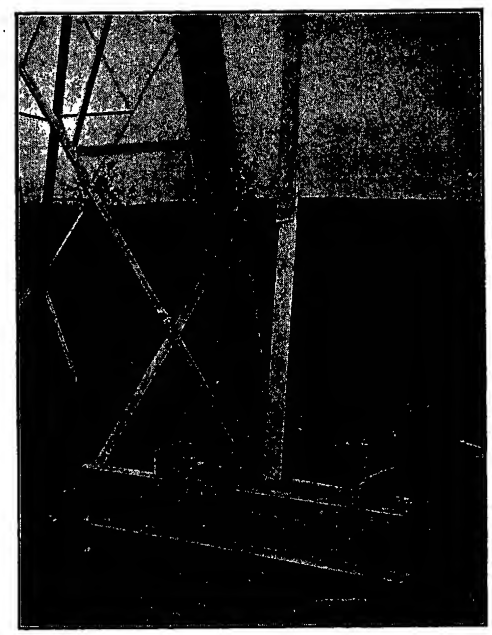

Fig. 18—Illustrating Installation of Typical Rock Footing

Picture taken before final grouting-in of footing. Note adjustable telescopic-joint between stub-angle and tower leg

channel members, with the short stub-angles attached, were then placed and the templet erected. After all adjustment and leveling was complete, the bolt-holes were drilled and the legs anchored. With these footings, the telescopic joint eliminates any necessity of blasting to get all footings at the same elevation (Fig. 18).

Towers were erected by tower-erection gangs following the footing gangs, usually moving ahead into the various camps as the footing gang vacated them. Towers were assembled in panels on the ground, which were then lifted into place by means of a 30-ft. gin pole. When one section was completed, the gin pole was raised and held in place by tackle which allowed it to be moved from one side of the tower to the other at will. The last section to be lifted in place was the center portion of the head.

Great care was taken with the galvanizing, so that in order to eliminate drifting all towers were at

first "loose-bolted." No wrenches that had a cutting edge, such as the alligator wrench, were used. Time studies on standard towers showed that it took approximately 100 man-hours to complete the erection.

Stringing was carried out by stringing crews of from 60 to 70 men. Insulators were hung first, and wood or aluminum-sheave pulleys attached in the clamp position. Conductors were then paid out through the sheaves, particular attention being paid to the cable so as not to damage it in any way. Logs were usually placed in rocky ground to act as skids and so as to avoid contact with points of abrasion. The cable joints to complete approximately a five mile section were then made. This jointing was all done by special members of the stringing crews, trained for this operation.

Stringing to final tension was usually done with teams, although some has been done using a gasoline tractor. A considerable part of the country traversed did not allow of the use of the tractor, and the teams were found to be quite satisfactory. Sag sheets were provided, all sags being adjusted for stretch of the cable, as pre-stretching was not provided for.

Communication over the five-mile length of cable usually pulled to tension at one time was by means of telephone, the power conductors being used as the telephone wires. In this way, very good results were obtained, even when the conductors were lying on the ground.

Two trucks, and sometimes three, were attached to each gang, for material handling and transportation to and from the camps. These trucks were also hired by the day, including driver.

In general, the two circuits have been constructed with a spacing of 150 ft. between circuits. This spacing was decided upon after discussion of the possibility of single lightning disturbances affecting both circuits simultaneously. The desirability of having the two circuits on one right-of-way was stressed, for ease of patrol and to avoid duplication of the telephone service, and it was finally decided that this separation would appear to be sufficient to avoid the above contingency.

The progress of construction of the first circuit was very definitely scheduled, as a particular date on which power delivery would commence had to be met. Charts, showing the schedule for each operation, were drawn up, and the progress made during each week recorded. In this way, a continuous check of the progress was available, and the speed of progress could be regulated to insure safely meeting the date specified. The second circuit schedule has been much less exacting, the work being carried steadily forward with the personnel trained during the erection of the first circuit. Record of progress is still maintained, however, in order to provide a check on the various field organizations.

Operation

The first unit of this 220,000-volt system, consisting of one transmission circuit and two banks of transformers at Leaside, was placed in service on October 1, 1928. The initial tests were carried out on September 23, 1928, at which time the entire transmission circuit and station bus work was energized to approximately 300,000 volts.

The western half of the second circuit was completed on October 1, 1929, since which time, in order to obtain the benefit of its conductivity, it has operated connected in parallel with the first circuit. The remainder of this circuit, and the installation of the third and fourth banks at Leaside, is scheduled for completion by October 1, 1930.

Between October 1, 1928 and April 1, 1930, ten line outages have occurred. These outages are classified as follows:

Three—due to insufficient clearance to trees, the clearing not having been completed when line was placed in service.

One —due to klydonograph connection breaking loose in a gale.

Four —during lightning storms, two being single-wire grounds, one a two-wire ground, and one a three-wire ground with very little ground fault current.

Two —not due to outside causes.

Except in one case, no permanent damage has resulted, the line returning to service immediately, the exception being when a conductor was actually broken by a tree felled by an inexperienced workman directly contrary to his foreman's orders. In the case of lightning flashovers, none of these have ever been definitely located.

Six flashovers occurred on the indoor 13,200-volt equipment during the early operating period, some of them involving two phases simultaneously. These flashovers were due to condensation of moisture in the newly completed building; this has since been eliminated, but the disturbance was so slight that the source of trouble was not located until the sixth flashover.

Except for some minor adjustments, the relay installation has given very satisfactory service. When trouble has occurred, the relay indicators have been found to give very valuable information as to the location and nature of the disturbance.

It has been found that the whole 230-mi. line can be energized or de-energized without disturbance to the remainder of the 110,000-volt system; in fact, no more precaution seems necessary than in switching a short section of 110,000-volt line.

Synchronizing the two systems at Leaside is extremely simple. On occasions when the systems have separated, they have been re-synchronized in two minutes.

From October 1, 1928 to September 15, 1929, a contract allotment of 80,000 hp. was carried over the single circuit, although momentary swings considerably in excess of 100,000 hp. were experienced. From September 15 to October 1, 1929, 130,000 hp. was carried over the single circuit without the aid of syn-

chronous condensers at Leaside. Since that time, a contract allotment of 150,000 hp. has been carried over the one and one-half circuit combination. For a short while, this load was also carried without the condensers, as unavoidable delays resulted in the condenser installation not being completed on schedule. At the present time, two of the 25,000-kv-a. units are in service.

Omitting the short period immediately following the placing into service of this system, a period of adjustment which all new systems suffer, the operation of the 220,000-volt system has been generally excellent, and may be very favorably compared with any section of the 110,000-volt system.

Future Developments

At the time the contract was entered into with the Gatineau Power Company, the block of 260,000 hp. purchased was estimated as sufficient to provide for the Niagara System growth to 1931. Present indications are that this block will all be absorbed in 1930, and progress is being made on other developments to be completed in 1931.

The Ottawa River forms the interprovincial boundary between the provinces of Ontario and Quebec, and its power sites are therefore under the joint jurisdiction of the two provinces. Development of these sites is necessarily a joint undertaking between the owners of the waterpower rights in the respective provinces.

Development of the Chats Falls site is proceeding on this basis, the site being adjacent to the Ottawa River crossing of the present 220,000-volt lines. The Hydro-Electric Power Commission is the Ontario owner of the waterpower rights at this site, and a contract has been entered into with the Quebec owners, so that all the power available will be delivered to the Niagara System.

The total amount of power involved is some 200,000 hp., and it is expected that two more 220,000-volt circuits will be built to Toronto, construction of the first of these to commence late this year. The lines from the Gatineau Power Company will be interconnected at Chats Falls, making a four-line 220,000-volt system for some 460,000 hp.

The first of the Chats Falls power will be delivered in 1931, and additional transformer capacity will be added at the Leaside Transformer Station to provide for this. Transformation will be to 110,000 volts, so that the power may be transmitted over the existing facilities to the other Toronto Transformer Stations.

It is not at present expected that the full amount of power from Chats Falls will be taken into Leaside, completing it to its full capacity of 360,000 kv-a., but that rather a second 220,000-volt transformer station will be built in the Toronto area. The site for this station has not been selected, but studies are under way in this regard.

A contract has also been entered into with the Beauharnois Light, Heat, and Power Company, for the delivery of 250,000 hp., commencing in 1932, and providing for installments up to the full amount in 1936. This company will develop power in the Lake St. Francis-Lake St. Louis portion of the all-Canadian section of the St. Lawrence River. Delivery will also be to Toronto, over 220,000-volt circuits approximately 300 miles long. This power will be transformed in the second 220,000-volt transformer station mentioned above.

Within the next five or six years, there will be six 220,000-volt circuits entering the Toronto area, representing some 1400 circuit-miles of 220,000-volt lines, with two transformer stations totaling in capacity approximately 540,000 kv-a. For a few years, all of the Toronto area demand will be supplied from eastern sources, with a surplus to be transmitted west from Toronto over the existing 110,000-volt lines from Niagara Falls. This western feed of power will be only a temporary condition, as Toronto's own growth will soon absorb the surplus. It is this fact which dictates the location of the second station in Toronto, rather than farther west. The choice of this second station location is an interesting problem, as the location must be such as to meet the estimated load requirements of the Toronto area, and yet not necessitate too great an outlay to provide for this temporary condition.

Acknowledgments

The author wishes to express his appreciation of the valuable assistance given by Messrs. A. H. Hull, E. A. Davison, and A. H. Frampton in the preparation of this paper.

Bibliography

1. *Metal-clad, Gum-filled Switchgear*, by L. B. Chubbuck, presented at the Summer Convention of A. I. E. E., 1930.

2. *The 25,000-Kv-a. Vertical-shaft, Synchronous Condensers, 25-Cycle, 500 Rev. Per Min., Outdoor Type for the Toronto-Leaside Transformer Station*, by R. E. Day, H. A. Ricker, and J. R. Dunbar, presented at the Summer Convention of A. I. E. E., 1930.

3. *Coordination of Insulation as a Design Problem*, by G. D. Floyd, presented at the Summer Convention of A. I. E. E., 1930.

4. "The Protective Relay Installation at the Toronto-Leaside Transformer Station of the Hydro-Electric Power Commission of Ontario," by E. M. Wood, *Journal* of the Engineering Institute of Canada, March 1929.

5. "Aerial Survey for Transmission Line Location," by A. C. Goodwin, *Bulletin* of the Hydro-Electric Power Commission. October 1927.

Discussion

M. M. Samuels: Mr. Brandon's paper would seem the beginning of a new era in plant description, it is by far the most complete and most systematic presentation of its kind that has ever come to my notice and I want to congratulate Mr. Brandon particularly on the manner of his presentation. It is more than a paper, it is both a textbook on modern high tension construction and a textbook on how to write up a description of a new plant. There is an abundance of new ideas, a great many radical and interesting departures from conventional

designs, many refreshingly courageous innovations and in each case there is not only a clear and concise description of the particular detail, but the reasons for it are also given, and the history of it is given together with descriptions of other methods which were considered and abandoned, together with the reasons why they were abandoned. Cost data would indeed be very interesting, but perhaps this is not within the range of an Institute paper, and furthermore cost data would reduce the attention which should be given to the overwhelming amount of design data. Too much discussion is being devoted nowadays to costs, even where the cost is of little consequence, and too little to design features. I suggest that the editing committee request future contributors that they use Mr. Brandon's paper as a guide for the set-up of descriptions of interesting new installations.

E. T. J. Brandon: It is indeed gratifying to receive such tribute as that rendered by Mr. Samuels in his discussion. One is frequently in doubt as to just how much detail should be included in such a paper, but it would appear that a happy solution has been obtained in this case.

Since the time of writing the paper the 220,000-volt system has operated without disturbance from any source. It must be admitted that the present lightning season has been somewhat below the average in number and severity of storms, but it is now possible to say that on August 24th, 1930, the system completed one whole year's operation without a single interruption due to external causes. This record reduces the average of interruptions on the 220,000-volt system, with practically two complete years of service, to 1.85 per 100 miles per year due to all causes, and 0.75 per 100 miles per year due to lightning flashovers alone.

The Analytics of Transmission Calculations

The Theoretical Foundation of the Quaternary Linear Real Transformation Connecting Input and Output Quantities in the General Electric Circuit Together with Its Application by Algebraic and Geometrical Methods

BY T. R. ROSEBRUGH*

Member, A. I. E. E.

***Synopsis.**—This paper deals mainly with a more general and systematic method of handling certain classes of problems involving steady state transmission calculations in terms of real quantities than has hitherto been used.*

Part I is introductory, however, and shows that the binary linear transformation which the writer showed in 1919 to exist for all ladder circuits in terms of complex quantities, and with determinant unity, occurs also in operational form for the general input—output network and likewise with determinant unity, thus including sine-wave as a particular case.

Part II views the general case of input-output circuits under sine wave conditions as a quaternary linear transformation in real quantities, likewise with determinant unity, but subject to a certain condition ("absolute covariant").

The subject matter involves on equal terms voltage-squared (z), current-squared (w), power (x), reactive voltamperes (y) for both input and output ends in the general circuit, and in the special case of a transmission line per se it also introduces mean values of these quantities throughout the length of the line, suggesting the engineering importance of some of them.

For this latter purpose the sixteen real coefficients of the transformation are given as functions of s the length of the line leading to their mean values as tabulated.

Twenty identities involving values of the "a-set" of coefficients are given which are useful for checking numerical values and simplifying unnecessarily cumbrous results.

The relations between the "a-set" and the "b-set" coefficients are given. The diagram of the admittance-plane is used and it is pointed out that it is also a three-origin vector diagram, the exact interpretation being given. A table of statistical data about the points of a "kite framework" shows the proportionate values of each of the eight fundamental quantities at each of these points in extremely simple form. There are eight fundamental circles in the plane and 28 families of simple ratio-loci (circles) each family having its own radical axis. About half of these have obviously useful conceptions either in power or in communication engineering.

A wider point of view is now introduced in which linear functions of the eight fundamental quantities are dealt with. A classification is made of problems of complete and incomplete data. The former may or may not involve maximum conditions. Problems of maxima may be one-conditioned or two-conditioned.

The type-cases of each are studied and the other cases reduced to the type.

One-conditioned maxima are associated graphically with (Poncelet's) limit-points and analytically with a matrix which defines a line and three circles intersecting in these limit-points.

Two-conditioned maxima are represented graphically by the points of intersection of a circle cutting three others orthogonally, with one of the circles. Analytically the determinantal equation, rules for whose formation are given in each case, gives the radical center and the radius of the circle intersecting the other orthogonally.

Two simple examples are worked out algebraically and arithmetically. *Acknowledgment is made of the assistance of Mr. V. G. Smith and Mr. G. DeB. Robinson.*

Part I

THE present paper deals with the general case of an electric system with input and output terminals, having constant coefficients, when in the steady state. It has reference mainly to a system of calculation in terms of real quantities by means of a quaternary linear transformation conditioned by a quadratic covariant.

While several papers,[1,2,3,4,5] dealing with certain problems of this kind in terms of real quantities, have already appeared, this paper is intended, within limits which will appear later, as a systematic study of the whole subject with a view to the greatest possible generality of treatment.

2. The binary substitution or transformation in complex quantities

$$\left.\begin{aligned} E_1 &= a\,E_0 + b\,I_0 \\ I_1 &= c\,E_0 + d\,I_0 \end{aligned}\right\} \qquad (1)$$

whereby two input quantities E_1 and I_1 are obtainable from the two output quantities E_0 and I_0 is now fairly well known.

The author has shown[6] that this transformation together with its inverse namely

$$\left.\begin{aligned} E_0 &= d\,E_1 - b\,I_1 \\ I_0 &= -\,c\,E_1 + a\,I_1 \end{aligned}\right\} \qquad (2)$$

would lead to many practical conclusions with regard to the behavior of series and parallel combinations of transmission lines, transformers, tie lines, etc., as well

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1. H. B. Dwight, *Elec. Jour.*, Aug. 1914, Vol. XI, p. 487.
2. R. D. Evans and H. K. Sels, *Power Limitations of Transmission Systems*, A. I. E. E. TRANS., 1924, Vol. 43, p. 26.
3. C. L. Fortescue and C. F. Wagner, *Some Theoretical Considerations of Power Transmission*, A. I. E. E. TRANS., 1924, Vol. 43, p. 16.
4. E. B. Shand, *The Limitations of Output of a Power System Involving Long Transmission Lines*, A. I. E. E. TRANS., 1924, Vol. 43, p. 59.
5. R. D. Evans and R. C. Bergvall, *Experimental Analysis of Stability and Power Limitations*, A. I. E. E. TRANS., 1924, Vol. 43, p. 39.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

6. *"The Calculation of Transmission Line Networks"* Bulletin No. 1, 1919, School of Engineering Research, University of Toronto.

as theoretically at least to solve some problems on the general network of which the units consist of such items. Some of these facts about circuits have now become widely known through the publications[7] of the Westinghouse Company.

3. It is fundamental in the establishment of these formulas that the determinant $a\,d - b\,c$ is unity. In the paper of 1919 referred to this is proved for quite general circuits but still not so general as the case of the general circuit of constant coefficients, and of any number of meshes and any couplings between meshes. It will therefore be shown in the next section how the proof may be extended to include such cases.

4. For a circuit of any number of meshes and having in general localized resistance inductance, and capacity, and coupled in any manner by such means and by mutual inductance and having only two meshes in which external e. m. f. is impressed called respectively the input and the output, the n differential equations as is well known may be written

$$\sum_{s=1}^{n} f_{rs}\, q_s = e_r, \quad (r = 1, 2 \ldots n) \tag{3}$$

where
$$f_{rs} = f_{sr} = a_{rs}\, p^2 + b_{rs}\, p + c_{rs} \tag{4}$$

These are in fact direct consequences of "Lagrange's Equations of Motion in Generalized Coordinates" and here two only of the set e_r differ from zero, say e_2 and e_1 (input and output).

Now treating these equations as though they were algebraical instead of differential equations, and solving for q_1 and q_2

$$\begin{aligned} q_1 D &= e_1 F_{11} + e_2 F_{21} \\ q_2 D &= e_1 F_{12} + e_2 F_{22} \end{aligned} \tag{5}$$

in which the "F" quantities are the corresponding co-factors to the "f's" and D is the determinant of the "f's." Put $-e_1 = e_1'$.

Then

$$\left.\begin{aligned} e_2 &= \frac{F_{11}}{F_{21}}\, e_1' + \frac{D}{F_{21}}\, q_1 &&= a'\, e_1' + b'\, q_1 \\ q_2 &= \left(\frac{F_{11}\, F_{22}}{F_{21}\, D} - \frac{F_{12}}{D}\right) e_1' + \frac{F_{22}}{F_{21}}\, q_1 &&= c'\, e_1' + d'\, q_1 \end{aligned}\right\} \tag{6}$$

Then
$$\begin{vmatrix} a', b' \\ c', d' \end{vmatrix} = \frac{F_{12}}{F_{21}} = 1 \tag{7}$$

Now put
$$i_1 = p\, q_1,\; i_2 = p\, q_2$$

then
$$\left.\begin{aligned} e_2 &= a'\, e_1' + \frac{b'}{p}\, i_1 = a\, e_1' + b\, i_1 \\ i_2 &= p\, c'\, e_1' + d'\, i_1 = c\, e_1' + d\, i_1 \end{aligned}\right\} \tag{8}$$

Then
$$\begin{vmatrix} a, b \\ c, d \end{vmatrix} = 1 \tag{9}$$

$\therefore$ That is $a\,d - b\,c = 1$

Here a, b, c, and d are rational functions of p the time-differentiator. This relation true for all operational values of p will then hold for the special equivalent $\omega\, j$. Thus the truth of this equation is established for the case of sine-wave.

Part II

5(a). There are great advantages to be gained by proceeding in a uniform and symmetrical manner to develop the consequences of Equation (1) fully with regard to the values of four homogeneous real quantities at both ends of the circuit, namely voltage-squared, current-squared, power and reactive volt-amperes. Individual formulas have been used by previous writers but a consideration of the set of relations as a whole is the guiding idea in what follows.

Another advantage of the more general point of view here presented is that by the use of twenty algebraic identities thereby developed many expressions may be greatly simplified.

From the two Equations (1) expressing the binary linear transformation, may be deduced the quaternary linear transformation in real quantities which in combination with the equation of its covariant is to be the subject of Part II. The procedure is as follows:

From Equations (1) deduce Equations (10) by taking the conjugate of each quantity on the left hand side. Conjugates are here denoted by a circumflex. Thus

$$\left.\begin{aligned} E_1 &= a\, E_0 + b\, I_0 \\ I_1 &= c\, E_0 + d\, I_0 \end{aligned}\right\} \text{(1) bis.} \quad \left.\begin{aligned} \hat{E}_1 &= \hat{a}\, \hat{E}_0 + \hat{b}\, \hat{I}_0 \\ \hat{I}_1 &= \hat{c}\, \hat{E}_0 + \hat{d}\, \hat{I}_0 \end{aligned}\right\} \tag{10}$$

Hence, expressing the four products obtained by taking each of the quantities on the left of one set multiplied into each of the like quantities of the other, four equations are obtained giving values in terms of similar quantities from the right hand side. The coefficients will be sixteen quantities similar to $a\,\hat{a}$.

On making the substitutions

$$E_0\, \hat{E}_0 = z,\; I_0\, \hat{I}_0 = w,\; I_0\, \hat{E}_0 = x + y\, j,\; \hat{I}_0\, E_0 = x - y\, j \tag{11}$$

$$E_1\, \hat{E}_1 = z',\; I_1\, \hat{I}_1 = w',\; I_1\, \hat{E}_1 = x' + y'\, j,\; \hat{I}_1\, E_1 = x' - y'\, j$$

the quaternary linear real transformation is obtained in the form

$$\begin{aligned} z' &= a_{11}\, z + a_{12}\, w + a_{13}\, x + a_{14}\, y \\ w' &= a_{21}\, z + a_{22}\, w + a_{23}\, x + a_{24}\, y \\ x' &= a_{31}\, z + a_{32}\, w + a_{33}\, x + a_{34}\, y \\ y' &= a_{41}\, z + a_{42}\, w + a_{43}\, x + a_{44}\, y \end{aligned} \tag{12}$$

7. "Electrical Characteristics of Transmission Circuits," by Westinghouse Engineers—William Nesbit, 1926.

The sixteen coefficients may be expressed as follows (if $a = a_0 + a_1 j$, $b = b_0 + b_1 j$, $c = c_0 + c_1 j$, $d = d_0 + d_1 j$)

$a_{11} = a_0^2 + a_1^2$	$a_{12} = b_0^2 + b_1^2$	$a_{13} = 2(a_0 b_0 + a_1 b_1)$	$a_{14} = 2(b_0 a_1 - a_0 b_1)$
$a_{21} = c_0^2 + c_1^2$	$a_{22} = d_0^2 + d_1^2$	$a_{23} = 2(c_0 d_0 + c_1 d_1)$	$a_{24} = 2(d_0 c_1 - c_0 d_1)$
$a_{31} = c_0 a_0 + c_1 a_1$	$a_{32} = d_0 b_0 + d_1 b_1$	$a_{33} = 1 + 2(a_1 d_1 + b_0 c_0)$	$a_{34} = 2(d_0 a_1 - b_1 c_0)$
$a_{41} = a_0 c_1 - c_0 a_1$	$a_{42} = b_0 d_1 - d_0 b_1$	$a_{43} = 2(a_0 d_1 - b_1 c_0)$	$a_{44} = 1 + 2(a_1 d_1 - b_1 c_1)$

(13)

Again starting from the inverse binary transformation (2) the inverse quaternary transformation is found which may be denoted by

$$\begin{aligned} z &= b_{11} z' + b_{12} w' + b_{13} x' + b_{14} y' \\ w &= b_{21} z' + b_{22} w' + b_{23} x' + b_{24} y' \\ x &= b_{31} z' + b_{32} w' + b_{33} x' + b_{34} y' \\ y &= b_{41} z' + b_{42} w' + b_{43} x' + b_{44} y' \end{aligned} \tag{14}$$

The values of the b-set when found are seen to be connected with the a-set by the following very simple relations:

$b_{11} = a_{22}$,	$b_{12} = a_{12}$,	$b_{13} = -2\, a_{32}$,	$b_{14} = -2\, a_{42}$
$b_{21} = a_{21}$,	$b_{22} = a_{11}$,	$b_{23} = -2\, a_{31}$,	$b_{24} = -2\, a_{41}$
$b_{31} = -\frac{1}{2}\, a_{23}$,	$b_{32} = -\frac{1}{2}\, a_{13}$,	$b_{33} = a_{33}$,	$b_{34} = a_{43}$
$b_{41} = -\frac{1}{2}\, a_{24}$,	$b_{42} = -\frac{1}{2}\, a_{14}$,	$b_{43} = a_{34}$,	$b_{44} = a_{44}$

(15)

These relations are for the most general input-output circuit and naturally lead to simpler ones where the circuit is symmetrical as in the case of the transmission line per se or the transmission line with similar transformers at both ends.

This may easily be shown to be identical with the cases where $a = d$.

In this case of input-output symmetry then the following additional relations hold:

$$\begin{aligned} a_{11} &= a_{22},\ a_{13} = 2\, a_{32},\ a_{14} = 2\, a_{42} \\ a_{23} &= 2\, a_{31},\ a_{24} = 2\, a_{41},\ a_{34} = a_{43} \end{aligned} \tag{16}$$

So that in this case the upper left and lower right quarters of the tables of the a-set and the b-set contain identical coefficients. The other eight pairs of a and b coefficients differ only in sign. This difference in sign is due to the convention with regard to current which is reckoned by an input rule of sense, at one end, and output at the other. The input rule of sense at both ends in the symmetrical circuit would identify completely the two sets of coefficients.

5(b). As an example the following are the values of the sixteen a-coefficients for the Paugan Falls-Leaside (Toronto) 25-cycle transmission line of the Hydro-Electric Power Commission of Ontario, the length of which is 229 miles, where the units are:—100,000 volts, 100 amperes, 10,000 kv-a.

a_{11}	a_{12}	a_{13}	a_{14}
0.961,71	0.006,438,0	0.053,583	−0.147,97
a_{21}	a_{22}	a_{23}	a_{24}
0.257,22	0.961,71	0.004,677,8	0.994,70
a_{31}	a_{32}	a_{33}	a_{34}
0.002,338,9	0.026,791	1.000,031,82	0.013,673
a_{41}	a_{42}	a_{43}	a_{44}
0.497,35	−0.073,984	0.013,673	0.923,38

These have been checked by a set of 10 identities.

6. Determinants. According to a theorem in determinants imputed to Kronecker by E. Pascal[8] the determinant of sixteen coefficients of type $a\,\hat{a}$ must be unity since it would be the product of the squares of the determinants of (1) and (10).

The determinant of the sixteen real coefficients a_{11} to a_{44} may then be shown to be unity also.

7. A covariant under the transformation.

There are fundamental facts with regard to the translation from complex form to real quantities expressible as follows:

$$\begin{aligned} w\, z &= I_0 \hat{I}_0 . E_0 \hat{E}_0 = I_0 \hat{E}_0 . \hat{I}_0 E_0 \\ &= (x + y j)(x - y j) = x^2 + y^2 \end{aligned} \tag{17}$$

$$\begin{aligned} w'\, z' &= I_1 \hat{I}_1 . E_1 \hat{E}_1 = I_1 \hat{E}_1 . \hat{I}_1 E_1 \\ &= (x' + y' j)(x' - y' j) = x'^2 + y'^2 \end{aligned}$$

that is

$$w\, z - x^2 - y^2 = 0 \tag{18}$$

$$w'\, z' - x'^2 - y'^2 = 0 \tag{19}$$

This suggests and it is in fact true that $w\, z - x^2 - y^2$ is an absolute covariant under the transformation (12). In ordinary language the situation is that the four Equations (12) when applied to any set of $z\, w\, x\, y$ will produce another possible (consistent) set of values for the b-end.

8. Consequences in twenty identities. Useful for checks of values of co-efficients and for simplifying formulas.

Since a, b, c, and d are complex quantities they are defined by eight real numbers, which, however, since $a\, d - b\, c = 1$ must be equivalent to six independent real parameters on which the sixteen coefficients of the a-set depend.

There must therefore be ten independent relations between these sixteen coefficients. These ten identities are then to be found by noting the conditions which are consequences of the covariance of $w\, z - x^2 - y^2$.

8. E. Pascal, "I Determinanti," Milan 1897. But it is not to be found in Kronecker's "Werke."

By substituting for $w' z' - x^{2\prime} - y^{2\prime}$ in terms of w, z, x and y by (12) and identifying the result with $w z - x^2 - y^2$ the following ten identities are obtained:

$$a_{31}^2 + a_{41}^2 - a_{11} a_{21} = 0 \qquad (20)$$

$$a_{32}^2 + a_{42}^2 - a_{12} a_{22} = 0 \qquad (21)$$

$$a_{33}^2 + a_{43}^2 - a_{13} a_{23} = 1 \qquad (22)$$

$$a_{34}^2 + a_{44}^2 - a_{14} a_{24} = 1 \qquad (23)$$

$$a_{11} a_{12} + a_{12} a_{21} - 2 a_{31} a_{32} - 2 a_{41} a_{42} = 1 \qquad (24)$$

$$a_{11} a_{23} + a_{13} a_{21} - 2 a_{31} a_{33} - 2 a_{41} a_{43} = 0 \qquad (25)$$

$$a_{11} a_{24} + a_{14} a_{21} - 2 a_{31} a_{34} - 2 a_{41} a_{44} = 0 \qquad (26)$$

$$a_{12} a_{23} + a_{13} a_{22} - 2 a_{32} a_{33} - 2 a_{42} a_{43} = 0 \qquad (27)$$

$$a_{12} a_{24} + a_{14} a_{22} - 2 a_{32} a_{34} - 2 a_{42} a_{44} = 0 \qquad (28)$$

$$a_{13} a_{24} + a_{14} a_{23} - 2 a_{33} a_{34} - 2 a_{43} a_{44} = 0 \qquad (29)$$

Again by making similar use of (14) another set of ten identities as follows are obtained:

$$a_{23}^2 + a_{24}^2 - 4 a_{21} a_{22} = 0 \qquad (30)$$

$$a_{13}^2 + a_{14}^2 - 4 a_{11} a_{12} = 0 \qquad (31)$$

$$a_{33}^2 + a_{34}^2 - 4 a_{31} a_{32} = 1 \qquad (32)$$

$$a_{43}^2 + a_{44}^2 - 4 a_{41} a_{42} = 1 \qquad (33)$$

$$2 a_{22} a_{11} + 2 a_{12} a_{21} - a_{23} a_{13} - a_{24} a_{14} = 2 \qquad (34)$$

$$2 a_{22} a_{31} + 2 a_{32} a_{21} - a_{23} a_{33} - a_{24} a_{34} = 0 \qquad (35)$$

$$2 a_{22} a_{41} + 2 a_{42} a_{21} - a_{23} a_{43} - a_{24} a_{44} = 0 \qquad (36)$$

$$2 a_{12} a_{31} + 2 a_{32} a_{11} - a_{13} a_{33} - a_{14} a_{34} = 0 \qquad (37)$$

$$2 a_{12} a_{41} + 2 a_{42} a_{11} - a_{13} a_{43} - a_{14} a_{44} = 0 \qquad (38)$$

$$2 a_{32} a_{41} + 2 a_{42} a_{31} - a_{33} a_{43} - a_{34} a_{44} = 0 \qquad (39)$$

These evidently must be equivalent to the first set but are nevertheless as useful practically.

In obtaining formulas for particular conditions it often occurs that very great simplification in the result may be attained by their use. For example:

Suppose one wished to know the value of $y' \div z$ under conditions of maximum power x' received for fixed transmitting z. Its value is

$$a_{41} + a_{42} \div (4\ a_{32}^2) + (2\ a_{42}\ a_{31} - a_{43}\ a_{33} - a_{44}\ a_{34}) \div (2\ a_{32})$$

But by using identity (39) it is found that all but the second term $a_{42} \div (4 a_{32}^2)$ is identically zero.

These identities are also of value in checking the accuracy of the sixteen coefficients.

9. There may be instances where mean values of current-squared, voltage-squared, etc., along a transmission line are desired. The former is a measure of the conductor line loss as well as the line reactive volt-amperes due to inductance. The latter measures the reactive volt-amperes due to capacity as well as the insulation loss, if any, and may then perhaps serve also as a suitable comparative measure of the load to which the line insulators are subject if a single number is desired for this purpose. For this purpose the sixteen coefficients must be regarded not as the constants which they are in the case of the length of the whole line, ($s = 1$), but as functions of the variable s for the point in question. Hence the set of four fundamental quantities, z', w', x', y', are likewise functions of s. Then if bars above the symbols denote the corresponding quantities

$$\bar{z} = \int_0^1 z' \, d s = z \int_0^1 a_{11} \, d s + w \int_0^1 a_{12} \, d s$$

$$+ x \int_0^1 a_{13} \, d s + y \int_0^1 a_{14} \, d s \qquad (40)$$

similarly for the others, and if we write

$$\int_0^1 a_{11} \, d s = \bar{a}_{11} \text{ etc.}$$

then

$$\begin{aligned} \bar{z} &= \bar{a}_{11} z + \bar{a}_{12} w + \bar{a}_{13} x + \bar{a}_{14} y \\ \bar{w} &= \bar{a}_{21} z + \bar{a}_{22} w + \bar{a}_{23} x + \bar{a}_{24} y \\ \bar{x} &= \bar{a}_{31} z + \bar{a}_{32} w + \bar{a}_{33} x + \bar{a}_{34} y \\ \bar{y} &= \bar{a}_{41} z + \bar{a}_{42} w + \bar{a}_{43} x + \bar{a}_{44} y \end{aligned}$$

In order to find these sixteen new coefficients conveniently introduce the following abbreviations:

$$A_0 + B_0 j = \sqrt{(R + X j)(G + B j)} \qquad (42)$$

$$m + n j = \sqrt{Z} \div \sqrt{Y} \qquad (43)$$

$$p + q j = \sqrt{Y} \div \sqrt{Z} \qquad (44)$$

$$\lambda = \frac{1}{2} (\cosh 2 A_0 s - \cos 2 B_0 s) \qquad (45)$$

Then at any point s units from A where unity is the length of the line we have

$$a_{11} = \frac{1}{2} \cosh 2 A_0 s + \frac{1}{2} \cos 2 B_0 s \qquad (46)$$

$$a_{12} = (m^2 + n^2) \lambda \qquad (47)$$

$$a_{13} = m \sinh 2 A_0 s - n \sin 2 B_0 s \qquad (48)$$

$$a_{14} = - n \sinh 2 A_0 s - m \sin 2 B_0 s \qquad (49)$$

$$a_{21} = (p^2 + q^2) \lambda \qquad (50)$$

$$a_{22} = a_{11} \qquad (51)$$

$$a_{23} = p \sinh 2 A_0 s - q \sin 2 B_0 s \qquad (52)$$

$$a_{24} = q \sinh 2 A_0 s + p \sin 2 B_0 s \qquad (53)$$

$$a_{31} = \frac{1}{2} a_{23} \qquad (54)$$

$$a_{32} = \frac{1}{2} a_{13} \qquad (55)$$

$$a_{33} = a_{11} + (pm + q n) \lambda \qquad (56)$$

$$a_{34} = (q m - p n) \lambda \qquad (57)$$

$$a_{41} = \frac{1}{2} a_{24} \qquad (58)$$

$$a_{42} = \frac{1}{2} a_{14} \qquad (59)$$

$$a_{43} = a_{34} \qquad (60)$$

$$a_{44} = a_{11} - (p\, m + q\, n)\, \lambda \qquad (61)$$

10. If now $\bar{a}_{ij} = \int_0^1 a_{ij}\, d\, s$ and we put

$$\bar{\lambda} = \frac{1}{4\, A_0} \sinh\, 2\, A_0 - \frac{1}{4\, B_0} \sin 2\, B_0 \qquad (62)$$

we have mean values of the sixteen coefficients for the line:

$$\bar{a}_{11} = \frac{1}{4\, A_0} \sinh 2\, A_0 + \frac{1}{4\, B_0} \sin 2\, B_0 \qquad (63)$$

$$\bar{a}_{12} = (m^2 + n^2)\, \bar{\lambda} \qquad (64)$$

$$\bar{a}_{13} = \frac{m}{2\, A_0} (\cosh 2\, A_0 - 1) + \frac{n}{2\, B_0} (\cos 2\, B_0 - 1) \quad (65)$$

$$\bar{a}_{14} = - \frac{n}{2\, A_0} (\cosh 2\, A_0 - 1) + \frac{m}{2\, B_0} (\cos 2 B_0 - 1) \quad (66)$$

$$\bar{a}_{21} = (p^2 + q^2)\, \bar{\lambda} \qquad (67)$$

$$\bar{a}_{22} = \bar{a}_{11} \qquad (68)$$

$$\bar{a}_{23} = \frac{p}{2\, A_0} (\cosh 2\, A_0 - 1) + \frac{q}{2\, B_0} (\cos 2\, B_0 - 1) \quad (69)$$

$$\bar{a}_{24} = \frac{q}{2\, A_0} (\cosh 2\, A_0 - 1) - \frac{p}{2\, B_0} (\cos 2\, B_0 - 1) \quad (70)$$

$$\bar{a}_{31} = \frac{1}{2}\, \bar{a}_{23} \qquad (71)$$

$$\bar{a}_{32} = \frac{1}{2}\, \bar{a}_{13} \qquad (72)$$

$$\bar{a}_{33} = \bar{a}_{11} + (p\, m + q\, n)\, \bar{\lambda} \qquad (73)$$

$$\bar{a}_{34} = (q\, m - p\, n)\, \bar{\lambda} \qquad (74)$$

$$\bar{a}_{41} = \frac{1}{2}\, \bar{a}_{24} \qquad (75)$$

$$\bar{a}_{42} = \frac{1}{2}\, \bar{a}_{14} \qquad (76)$$

$$\bar{a}_{43} = \bar{a}_{34} \qquad (77)$$

$$\bar{a}_{44} = \bar{a}_{11} - (p\, m + q\, n)\, \bar{\lambda} \qquad (78)$$

The loss of power in the line and the change in value of y is evidently given as follows:

$$x' = x + R\, \bar{w} + G\, \bar{z}$$
$$y' = y + B\, \bar{z} - X\, \bar{w} \qquad (79)$$

By solving the system of four pairs of equations which follow from these two equations, the following values of eight of the mean values may be found. These appear likely to be the most useful, and the check with the previous formulas may be applied. Where $K = 2\, A_0\, B_0$

$$\bar{a}_{11} = (a_{31}\, X + a_{41}\, R) \div K,\ \bar{a}_{21} = (a_{31}\, B - a_{41}\, G) \div K$$
$$\bar{a}_{12} = (a_{32}\, X + a_{42}\, R) \div K,\ \bar{a}_{22} = (a_{32}\, B - a_{42}\, G) \div K$$
$$\bar{a}_{13} = \{ (a_{33} - 1)\, X + a_{43}\, R \} \div K.$$
$$\bar{a}_{23} = \{ (a_{33} - 1)\, B - a_{43}\, G \} \div K$$
$$\bar{a}_{14} = \{ a_{34}\, X + (a_{44} - 1)\, R \} \div K,$$
$$\bar{a}_{24} = \{ a_{34}\, B - (a_{44} - 1)\, G \} \div K \qquad (80)$$

and therefore

$$K\, \bar{z} = X\, (x' - x) + R\, (y' - y),$$
$$K\, \bar{w} = B\, (x' - x) - G\, (y' - y) \qquad (81)$$

11. Just as in ordinary vector notation three numbers, namely the value of the current, the voltage, and the angle between their directions are necessary for specifying conditions at an end of a circuit, so here also three numbers are necessary and sufficient. Any three out of the four z, w, x, y, (barring the usual ambiguities arising from quadratics) will specify exactly the conditions. It may thence be seen that apart from possible ambiguity any three independent data about $z, w, x, y, z', w', x', y'$ (or for a simple transmission line, also $\bar{z}, \bar{w}, \bar{x}, \bar{y}$,) will fix all conditions. Thus if L_1, L_2, and L_3 be any three-linear functions of these eight (or twelve) variables, the fixing of these three L's will in general serve. For the points of a model to represent definite states of the circuit three dimensions would then be needed and the values of $L_1\, L_2$ and L_3 would serve to define a point, the "state-point" of the system such that all other numerical data would be implied by its position.

Using only the twelve quantities above, simplex, there would be 220 choices of such models. However, the combinations x, y, z, or $x'\, y'\, z'$ have evident advantages, though something might be said for certain other combinations.

Now in view of the fact that all the equations of the a-set, the b-set and those of the mean value quantities, and the covariant conditions, are homogeneous in the variables, it follows that the equations deal essentially with ratios, and that these all hold when every quantity involved, namely z, w, x, y, or $z', w', x', y', \bar{z}, \bar{w}, \bar{x}, \bar{y}$ and consequently also L_i (any homogeneous linear function of them) is multiplied by any common factor.

12. Any three-dimensional model of this type therefore will have the property that as the state-point moves on a straight line from the origin all the variables and hence all L's will vary in direct proportion to its distance from the origin. The essence of any such model will therefore consist in the direction of the line from the origin to the state-point and this is indicated by the intersection of this line with any fixed plane not through the origin.

The simplest plane of representation in the $x\ y\ z$ model would be a plane for constant z. This amounts to what has been called the "Evans and Sels modified

diagram." However, the three-dimensional model which has been suggested uses $|E|$, that is, in the present notation the square root of z for third dimension. This naturally does not possess the simple linear projective property described above.

Instead of straight lines in the model joining points, in the plane above mentioned, to the origin there would be parabolas and for circles in the plane instead of cones there would be complicated surfaces. Hence at least for visualization the model here proposed is preferable.

13. Now since all variables are functions of any three, and other consistent values of all may be found by using any constant factor, it follows that all ratios of variables are determined when any two ratios are given. It will also follow that if three ratios be given there will generally be an inconsistency in the data.

Taking $x \div z = u$ and $y \div z = v$, u and v are the representatives of x and y obtained by using the points where the line from the origin to the state-point $(x\, y\, z)$ intersects the plane $z = 1$.

Hence all the 28 ratios of the eight (or 66 of the twelve) variables have defined values for assigned u and v.

So far as ratios are concerned the state-point may now be thought of as in this plane. At any rate the perspective image of the state-point lies there.

14. Although all the quantities thus dealt with in the x, y or in the $u\, v$ plane are real, there are nevertheless vector relations at their basis which have not disappeared beyond recovery.

For $$E_1 = b \,.\, A\, S \,.\, E_0 \qquad (82)$$
and $$I_1 = d \,.\, B\, S \,.\, E_0 \qquad (83)$$

These relations which are to be interpreted vectorially may be obtained as follows:

For $$E_1 \div E_0 = b \,.\, (a/b + u + v\, j) \qquad (84)$$
and (as vector)
$$A\, O = (a_{13} + a_{14}\, j) \div 2\, a_{12} = a/b \qquad (85)$$
and $$u + v\, j = O\, S \qquad (86)$$
hence (82) is true.

Also $$I_1 \div E_0 = d \,.\, (c/d + u + v\, j) \qquad (87)$$
and (as vector)
$$B\, O = (a_{23} + a_{24}\, j) \div a_{22} = c/d \qquad (88)$$
hence (83) follows.

That is the vectors $A\, S$ and $B\, S$ defined by the state-point S fix E_1 and I_1 in proper vector relation to E_0 when respective base lines are used which take account of b and d respectively.

More precisely stated the vector ratio of E_1 to E_0 is that of $A\, S$ to $1/b$ and the vector ratio of I_1 to E_0 is that of $B\, S$ to $1/d$.

Thus a second interpretation which may be put on the u, v plane is that it is a three-origin vector diagram. That is to say O, A, and B are three origins from which vectors drawn to a point S represent correctly in magnitude and phase (when properly referenced) I_0, E_1, and I_1 respectively.

15. The framework. Eight circles. Continuing with the ideas of Sec. 13 with a view to the general treatment of Sec. 16, it is noted that the fundamental quantities individually present the simplest instance of a linear function of their own values.

Thus $z, w, x, y, z', w', x', y'$ are each an L where L denotes a linear homogeneous function of such quantities.

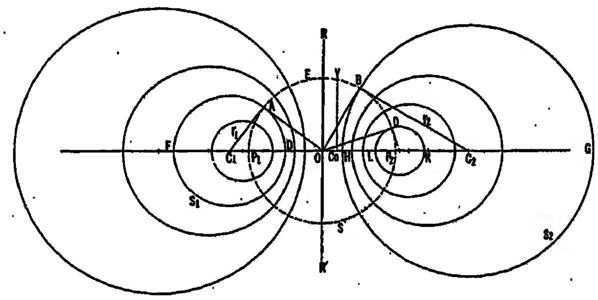

FIG. 1—SYSTEMS OF CIRCULAR LOCI WITH COMMON RADICAL AXIS AND r^2 POSITIVE. ALSO TYPE CASE $Q\, M_r$

Each of these is comprised in the equation
$$L \equiv a\, z + b\, w + c\, x + dy$$
where the coefficients are general.

Then putting as before $u = x \div z$, $v = y \div z$
$$S \equiv L \div z = a + b\,(u^2 + v^2) + c\, u + d\, v$$
Then $S = 0$ would, when $b \neq 0$, denote a circle in the u, v plane, and this will be the case for $z'\, w'\, x'\, y'$ and w, at least in a formal sense. Also S denotes for any given point (u, v) the square of the tangent to the

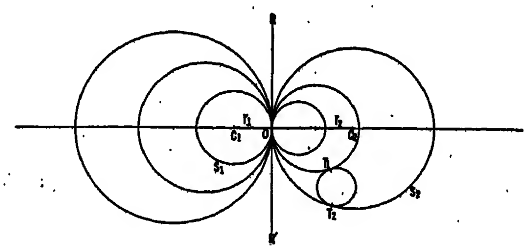

FIG. 2—SYSTEMS OF CIRCULAR LOCI WITH COMMON RADICAL AXIS AND r^2 ZERO

given circle multiplied by b when the point is external, or the negative of the square of half the chord which it bisects multiplied by b when it is internal to a real circle.

For $L = x$ and y respectively $S = u$ and v respectively. Thus $L = 0$, and hence $S = 0$ denotes, here, one of five circles or two straight lines, the axes.

The case $L = z$ gives $S = L \div z = 1 \neq 0$. This case is called in geometry the "line at infinity." Here a better name would be "circle at infinity."

The center of $S = 0$ is at $u = -c \div (2\, b)$, $v = -d \div (2\, b)$ and its radius squared is $(c^2 + d^2 - 4\, a\, b) \div (4\, b^2)$.

The quantity $c^2 + d^2 - 4\,a\,b$ on reference to identities (31) (30) (32) and (33) will be seen to have the values, 0, 0, 1 and 1 for z', w', x' and y' respectively. The radii for these circles will then be 0, 0, $1 \div (2\,a_{32})$ and $1 \div (2\,a_{42})$.

If now the centers of these circles, $S = 0$ for z', w', x' and y' be located in the plane with the coördinates,

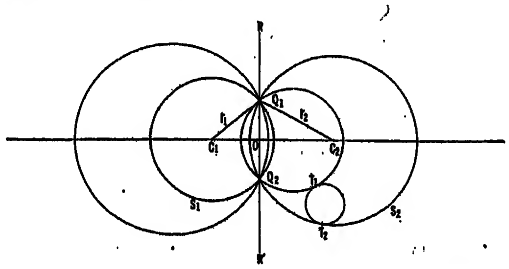

FIG. 3—SYSTEMS OF CIRCULAR LOCI WITH COMMON RADICAL AXIS AND r^2 NEGATIVE

$$\begin{aligned}
&\text{for} && z' = 0, \; -a_{13} \div (2\,a_{12}) \text{ and } -a_{14} \div (2\,a_{12})\\
&\text{"} && w' = 0, \; -a_{23} \div (2\,a_{22}) \text{ and } -a_{24} \div (2\,a_{22})\\
&\text{"} && x' = 0, \; -a_{33} \div (2\,a_{32}) \text{ and } -a_{34} \div (2\,a_{32})\\
&\text{"} && y' = 0, \; -a_{43} \div (2\,a_{42}) \text{ and } -a_{44} \div (2\,a_{42})
\end{aligned}$$

these centers will appear as in the "kite" framework shown in Fig. 4 at A, B, C, and D respectively. A and B will then be point circles while the circles $x' = 0$, $y' = 0$ must each pass through the points $z' = 0$, $w' = 0$, that is A and B.

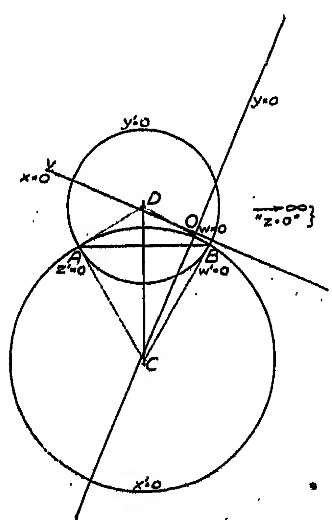

FIG. 4—THE FRAMEWORK. EIGHT CIRCLES THE BASIS FOR 28 FAMILIES OF CIRCULAR RATIO-LOCI

The other circles will be $w = 0$, a point circle at O the two axes as infinite circles and the "circle at infinity."

By use of (12) and the identities given, the relative values of the fundamental quantities at the centers $A\,B\,C\,D$ and O are as given in Table I where being relative only they have been arranged for convenience to avoid fractions.

TABLE I
RELATIVE VALUES OF

At	z	w	x	y	z'	w'	x'	y'
A	$2\,a_{12}$,	$2\,a_{11}$	$-\,a_{13}$	$-\,a_{14}$	0	2	0	0
B	$2\,a_{22}$,	$2\,a_{21}$	$-\,a_{23}$	$-\,a_{24}$	2	0	0	0
C	$4\,a_{32}^2$,	$1 + 4\,a_{31}\,a_{32}$,	$-\,2\,a_{33}\,a_{32}$,	$-\,2\,a_{34}\,a_{32}$,	a_{12}	a_{22}	$-\,a_{32}$	a_{42}
D	$4\,a_{42}^2$,	$1 + 4\,a_{41}\,a_{42}$,	$-\,2\,a_{43}\,a_{42}$,	$-\,2\,a_{44}\,a_{42}$,	a_{12}	a_{22}	a_{32}	$-\,a_{42}$
O	1	0	0	0	a_{11}	a_{21}	a_{31}	a_{41}

The distances in Fig. 4 are given as follows:

$$A\,B^2 = 1 \div (a_{12}\,a_{22}),\; A\,C^2 = B\,C^2 = 1 \div (4\,a_{32}^2)$$
$$A\,D^2 = B\,D^2 = 1 \div (4\,a_{42}^2)$$
$$C\,D^2 = a_{12}\,a_{22} \div (4\,a_{32}^2\,a_{42}^2),\; A\,O^2 = a_{11} \div a_{12}$$
$$B\,O^2 = a_{21} \div a_{22}$$
$$C\,O^2 = A\,C^2 + a_{31} \div a_{32},\; D\,O^2 = A\,D^2 + a_{41} \div a_{42}$$

Since $C\,D^2 = C\,A^2 + A\,D^2$, by using (21), the angle $C\,A\,D$ is a right angle and the circles $x' = 0$, $y' = 0$ intersect orthogonally.

16. I. Problems involving linear functions, L of the fundamental quantities z, w, x, and y in such a way as to lead to fixed values of them may be classified into three divisions, in each of which definite solutions

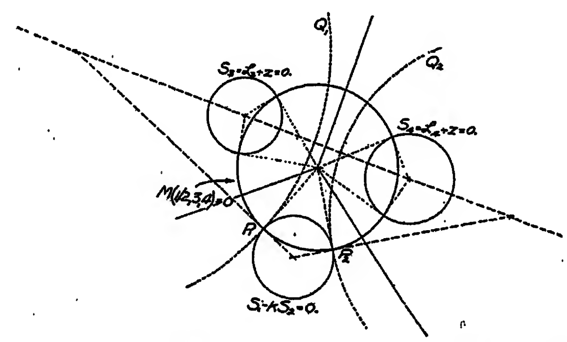

FIG. 5—TYPE CASE $Q^2\,M_r$. TWO QUANTITIES GIVEN. MAXIMUM OF RATIO AT $P_1\,P_2$

are possible both analytically and graphically. For simplicity the term maximum will here be used in place of extremum to include minimum.

(A) Three linear functions given numerically of which one at least is not zero.

(B) One-conditioned maximum. The type case is one linear function not zero given, and a ratio of two linear functions to have a maximum value.

(C) Two-conditioned maximum. The type case is two linear functions given of which one at least is not zero, and a ratio of two linear functions to have a maximum value.

II. Problems involving linear functions may also be presented with less data than as described above thus:

(D) Two linear functions given of which one at least is not zero.

(E) Two linear functions given equal to zero.

(F) One linear function given equal to zero.

While these do not lead to definite solutions they do lead to loci whose examination may be very instructive and yield much information.

17. Algebraic Solutions.

For convenience in the further examination of these six divisions let the linear functions be referred to as $L_1\, L_2$ etc. with numerical values denoted by q_1, q_2 etc.

Let Q denote a case of $L = q \neq 0$
O denote a case of $L = 0$
R denote a case of $L_1 \div L_2 = k$
M_q denote a maximum of a quantity.
M_r denote a maximum of a ratio.

An exponent is used to indicate the number of each kind of datum. Thus $Q^2\, O$ denotes a case where two linear functions not equal to zero are given and one that is zero.

I. (A) This case of three data may then occur in the forms Q^3, $Q^2\, O$, $Q\, O^2$ and to these may be added $Q^2\, R$ and $Q\, R^2$ because R means a relation of the type: $L_1 \div L_2 = k$, or $L_1 - k\, L_2 = 0$ that is $L = 0$ which is denoted by O.

In all these five cases then there are three equations such as

$$\begin{aligned} a_1 z + b_1 w + c_1 x + d_1 y &= q_1 \\ a_2 z + b_2 w + c_2 x + d_2 y &= q_2 \\ a_3 z + b_3 w + c_3 x + d_3 y &= q_3 \end{aligned} \tag{89}$$

of which not more than two values on the right may be zero. These are to be combined with

$$w\, z - x^2 - y^2 = 0 \tag{90}$$

This is readily done by obtaining linear expressions for w, x, and y from (89) in terms of z and these on substitution in (90) give a quadratic equation determining z and thence w, x, and y.

I. (B) One-conditioned maximum. Two subdivisions are (1), L_1, $L_2 \div L_3$ maximum, regarded as the type case $Q\, M_r$ and (2) $Q\, M_q$ which may also be presented in the form $Q\, M_r$.

For $Q\, M_q$ means $L_1 = q_1$, and L_2 to be maximum. Now this is equivalent to $L_2 \div L_1$ to be maximum. Hence it may be thus put into the form $Q\, M_r$.

A solution of the type case $Q\, M_r$ gives the following matrix equal to zero:

$$\begin{bmatrix} a_2 & b_2 & c_2 & d_2 \\ a_3 & b_3 & c_3 & d_3 \\ w & z & -2x & -2y \end{bmatrix} \tag{91}$$

in the sense that each of the three-rowed square determinants which can be made from it is zero. Omitting the first column the line of centers for the two circles S_2 and S_3 associated with L_2 and L_3 respectively is found and omitting any other column a circle is found which intersects this line of centers in the limit-points of the system.

For brevity the matrix conditions above (91) may be denoted by $M\,(2, 3) = 0$.

Then since the second case $Q\, M_q$ corresponds as mentioned above to a denominator L_1 instead of L_3 the condition for it must be $M\,(2, 1) = 0$.

In both these cases the matrix gives a linear and also a quadratic equation in u and v which are thus sufficient to determine them, and then the covariantive equation and the equation $L_1 = q_1$ together fix z, w, x and y.

I. (C) Two-conditioned maximum. The type case is $Q^2\, M_r$, the other cases being $Q^2\, M_q$, $Q\, O\, M_r$, $Q\, R\, M_r$, $Q\, R\, M_q$ and $Q\, O\, M_q$. For as in the previous divisions, an R condition may be put in the O form and an M_q in the M_r form.

Type case $Q^2\, M_r$: This denotes a problem of the form

$$L_1 = a_1 z + b_1 w + c_1 x + d_1 y = q_1$$
$$L_2 = a_2 z + b_2 w + c_2 x + d_2 y = q_2$$
$$L_3 \div L_4 = \frac{a_3 z + b_3 w + c_3 x + d_3 y}{a_4 z + b_4 w + c_4 x + d_4 y} \text{ to be maximum.}$$

Let $q_2 \div q_1 = k$, then $L_2 - k\, L_1 = 0$ is a homogeneous equation conditioning the maximum and it may be shown that $D\,(2 - k\,1, 3, 4) = 0$ is the solution where this for brevity denotes that the following determinant is zero:

$$\begin{vmatrix} a_2 - k\, a_1, & b_2 - k\, b_1, & c_2 - k\, c_1, & d_2 - k\, d_1 \\ a_3 & b_3 & c_3 & d_3 \\ a_4 & b_4 & c_4 & d_4 \\ w & z & -2x & -2y \end{vmatrix} = 0 \tag{92}$$

This may be expressed also as

$$D\,(2, 3, 4) = k\, D\,(1, 3, 4) \tag{93}$$

The other cases may then be dealt with as follows:

Case $Q^2\, M_q$:

Say that $L_1 = q_1$, $L_2 = q_2$ and that L_3 is to be maximum and therefore also $L_3 \div L_1$. L_1 now may replace L_4 and the equation becomes $D\,(2, 3, 1) = k\, D\,(1, 3, 1)$. But $D\,(1, 3, 1) = 0$ from the properties of determinants.

Therefore
$$D\,(2, 3, 1) = 0 \tag{94}$$

Case $Q\, O\, M_r$: This is $L_1 = q_1$, $L_2 = 0$, $L_3 \div L_4$ to be maximum.

That is to say a particular case of $Q^2\, M_r$ with $k = 0$. Hence the equation is
$$D\,(2, 3, 4) = 0 \tag{95}$$

Case $Q\, R\, M_r$: This is $L_1 = q_1$, $L_2 - k\, L_3 = 0$, $L_4 \div L_5$ to be maximum.

That is, it is a variant of $Q\, O\, M_r$ and the equation will be

$$D\,(2 - k\,3, 4, 5) = 0 \text{ or } D\,(2, 4, 5) = k\, D\,(3, 4, 5) \tag{96}$$

Case $Q\, R\, M_q$: This is $L_1 = q_1$, $L_2 - k\, L_3 = 0$, L_4 to be maximum.

Substituting for the latter $L_4 \div L_1$ to be maximum, the equation becomes

$$D\,(2 - k\,3, 4, 1) = 0, \text{ or } D\,(2, 4, 1) = k\, D\,(3, 4, 1) \tag{97}$$

Case $Q\, O\, M_q$: This is $L_1 = q_1$, $L_2 = 0$, L_3 to be maximum.

Since the conditions are as in $Q^2\, M_q$, with $k = 0$ (which however does not alter the result) the equation is

$$D\,(2, 3, 1) = 0 \tag{98}$$

18. Geometrical Solutions. The ratio relation $L_1 = k\, L_2$, leads to

$$S_1' - k\, S_2' = 0$$

and thus to the corresponding loci. As sufficient detail is not readily found, if at all, in standard works on analytical geometry, a classification of the different forms, real and imaginary, which the locus $S_1' - k S_2' = 0$ may assume, follows. It is useful in suggesting geometrical constructions.

Here $S_1' = b_1 (x^2 + y^2) + c_1 x + d_1 y + a_1$

$S_2' = b_2 (x^2 + y^2) + c_2 x + d_2 y + a_2$

Broadly speaking S_1' and S_2' may denote two straight lines ($b_1 = 0$, $b_2 = 0$) and finally two circles ($b_1 = 1$, $b_2 = 1$). In this latter case it will be more convenient by transforming to an origin at the center of S_1' and axis of abscissas through center of S_2', to replace S_1' and S_2' (when the distance between centers $C_1 C_2$ is equal to a) by the form

$$S_1 : x^2 + y^2 - r_1^2$$
$$S_2 : (x - a)^2 + y^2 - r_2^2$$

In the first eight cases below it is not difficult to determine the members of the system geometrically. In the remaining cases the geometrical constructions are for the most part cumbersome and it is desirable to determine the radical axis analytically. Its equation will be, in the new coordinates,

$$S_1 - S_2 = 0 \text{ or } 2\,a\,x = r_1^2 - r_2^2 + a^2 \qquad \textbf{(99)}$$

and this will intersect the line of centers at a point O

distant $\dfrac{a}{2} + \dfrac{r_1^2 - r_2^2}{2\,a}$ from the center C_1 of S_1.

Evidently the radical axis is always real. The limit points P_1, P_2 of the system will be given by the intersection of a circle S, center O and radius r, where

$$r^2 = \frac{a^2}{4} - \frac{1}{2}(r_1^2 + r_2^2) + (r_1^2 - r_2^2)^2 \div (2\,a) \qquad \textbf{(100)}$$

with the line of centers, $C_1 C_2$.

Hence the points P_1 and P_2 are real coincident, or imaginary according as r^2 is positive zero or negative, *i. e.* as O is exterior, on or interior to every circle of the system.

Two straight lines $b_1 = b_2 = 0$

(1) $c_1 = d_1 = c_2 = d_2 = 0$. Both at infinity. As the expressions are both constants there is no problem here.

(2) $c_1 = 0$, $d_1 = 0$, or else $c_2 = 0$, $d_2 = 0$. One only at infinity. The other members of the system are then parallel to that at finite distance.

(3) $d_1/c_1 = d_2/c_2$. Two parallel lines at a finite distance. The system consists of all lines parallel to them.

(4) $d_1/c_1 \neq d_2/c_2$. Two intersecting lines. The system consists of all lines through their intersection.

Straight line and a circle ($b_1 = 0$, $b_2 = 1$.)

(5) ($c_1 = 0$, $d_1 = 0$). Line at infinity and circle, (real, imaginary, or point). The system consists of all concentric circles (real, imaginary, or point).

(6) Line at finite distance and real circle which it intersects. The system consists of all circles through these points of intersection.

(7) Line at finite distance and real or point circle which it does not intersect. The system will consist of all the circles which taken with the given circle have the line as radical axis.

In Fig. 1, $R\,O\,R'$ is the given line, $D\,A\,F$ the given circle, center C_1, $C_1 O$ perpendicular to $R\,O\,R'$, $O\,A$ tangent to $D\,A\,F$ at A. The circle $P_1 E P_2$ center O determines the limit points $P_1 P_2$ which are the point circles of the system. This circle $P_1 E P_2$ is, further, orthogonal to every member of the system, some of which are shown in Fig. 1 and which of course have centers on the "line of centers" $P_1 O P_2$.

(8) Line at finite distance and imaginary circle. In Fig. 1 $R\,O\,R'$ is the given line, C_0 the center of the imaginary circle and $C_0 Y$ the amplitude of the imaginary radius, $C_0 O$ being perpendicular and $C_0 Y$ parallel to $R\,O\,R'$. The circle, center O, and radius $O\,Y$ determines P_1 and P_2 the point circles of the system and all others by the property of orthogonality as in Fig. 1.

Two Circles. $b_1 = b_2 = 1$.

(9) Two real circles intersecting in the points Q_1 and Q_2 (see Fig. 3). Here the point O is the midpoint of Q_1, Q_2, and r^2 is negative. All the circles of the system pass through Q_1 and Q_2 and have their centers on the line through O perpendicular to $Q_1 Q_2$.

(10) Two real non-intersecting circles $S_1 S_2$, external to each other as $D\,A\,F$, $G\,B\,H$ in Fig. 1. The point O may be determined by the formula possibly more easily than by graphical means and the orthogonal circle is real. The members of the system have their centers on $C_1 C_2$ and are orthogonal to S.

(11) Two real non-intersecting circles, S_1 being internal to S_2, as $K\,D\,L$, $G\,B\,H$ in Fig. 1. This case is essentially the same as the preceding, number (10), and the point O and S may be determined as before.

(12) Two real circles touching each other at the point O (Fig. 2). The radical axis consists of the common tangent, and every circle of the system is tangent to it at the point O. The circle S is now a point circle, $r^2 = 0$.

(13) One real circle as $D\,A\,F$ and one imaginary circle S_0, center C_0 and amplitude of imaginary radius $C_0 Y$, Fig. 1, where $C_0 Y$ is drawn perpendicular to $C_0 C_1$ and Y lies on S.

The center of S_0, namely C_0, may be outside on, or inside S_1, but in either case the radical axis is readily found by the formula or graphically and the circle S is always real.

(14) Two imaginary circles. Here both r_1^2 and r_2^2 are negative and r^2 is always positive.

19. Geometrical Solutions. Use of circular loci. The preceding section contains a classification of

loci corresponding to variable ratios of L_1 to L_2 according to the circular or linear characters of S_1 and S_2 corresponding to them. They correspond to the families of circles of which examples are to be seen in Figs. 1, 2, and 3. They are characterized by having a common radical axis associated with and determined by L_1 and L_2.

Cases O and R: Cases $L = 0$, and $L_1 - k\,L_2 = 0$ in which k is fixed, which correspond, to O and R of Sec. 17, may be represented geometrically by putting them in the form $S = 0$ from which the center and radius may be found as in Sec. 15 if it is a real circle, otherwise as a straight line by usual methods.

Section 17 I (A). Cases Q^3, $Q^2\,O$, $Q\,O^2$: These may for the present purpose all be expressed as $Q\,O^2$.

Each O will then define a circle (in general) which may be drawn. The intersection point or points will then give the values of u and v and thence all the ratios. The values are then given by Q, namely $L_1 = q_1$ that is $S_1\,z = q_1$ or $z = q_1 \div S_1$. Then q_1 being known and S_1 being a given function of u and v is known also for the intersection determined. Now that z is known the ratios found determine all the quantities.

Section 17 I (B). The type case of one-conditioned maximum $Q\,M_r$ viewed geometrically calls essentially for the maximum of a ratio to be determined, that is some limiting number for k in $S_2 - k\,S_3 = 0$ is to be found. Such numbers, however, do not exist when S_2 and S_3 belong to the families of circles shown in Fig. 2, intersecting in two points, or in Fig. 3 with common point of tangency, but only in Fig. 1. In Figs. 2 and 3, k may have any value while in Fig. 1 the limit points P_1 and P_2 correspond to extreme values of k.

If then L_2 and L_3 are related as in Fig. 1, and external to each other the radical axis $R\,O\,R'$ may be found since it bisects the common tangent and the two limit points are then on the line of centers at distance $O\,A$ from O where A is a point of tangency on either circle. In any case the formulas of Sec. 18 may be used to locate the limit points and thus all ratios. Then $z = q_1 \div S_1$ will give all the quantities required.

An approximation that may be convenient in a case of two circles relatively small and moderately distant, of radii r_1 and r_2 and distance between centers d, is that measuring along the line of centers from the first center the nearer limit-point is at the distance given by the continued fraction whose repeating period is $(r_1^2/d - r_2^2/d -)$.

Also if one be a circle of radius r and the other a straight line at distance p from the center then the nearer limit point will be at distance $p - \sqrt{p^2 - r^2}$ or if $r \div p = \sin\theta$ then at distance $2\,p\sin^2(\theta/2)$.

Section 17 I (C). Two-conditioned maximum. Type Case $Q^2\,M_r$. As before this means $L_1 = q_1$, $L_2 = q_2$ and $L_3 \div L_4$ to be maximum. Putting in the form $Q\,O\,M_r$ and leaving Q for final consideration, there remains $O\,M_r$. The equation O is $S_2\,q_1 - S_1\,q_2 = 0$, or say $S_{21} = 0$. M_r means $S_3 - m\,S_4 = 0$ with m a maximum. Consequently the extreme members of the family S_3, S_4 are sought which are consistent with S_{21} : a geometrical problem of three circles.

If S_3 and S_4 are given such as to belong to the system of Fig. 3, and S_{21} is the circle $T_1\,T_2$ then the graphical problem is to draw a circle through Q_1 and Q_2 the points of intersection of S_3 and S_4 so as to be tangent to the circle $T_1\,T_2$. This can be done in two ways and hence T_1, T_2 found, thus determining the ratios and then as above the quantities.

Similarly if S_3 and S_4 belong to the system of Fig. 2, two circles of the system tangent to their radical axis at O and also to the circle $T_1\,T_2$ at T_1 and T_2 respectively may be found graphically.

If, however, S_3 and S_4 belong to the system of Fig. 1, as in Fig. 5, then taking them with the other circle, namely $S_1 - k\,S_2$, pair by pair, they will have three radical axes meeting in a point, the radical center. This point has the property that a circle having it for center intersects orthogonally every member of each of the three systems of circles with these radical axes. Hence drawing tangents from the radical center to the circle $S_1 - k\,S_2$ the points (P_1, P_2) fulfill the required condition. The ratios are thus fixed and $z = q_1 \div S_1 = q_2 \div S_2$ then fixes the quantities.

In Section 16, II (D) (E) (F), cases $Q\,O$, O^2 and O are mentioned of data per se insufficient to determine a definite solution. Some of these arise from ratios; they may be $Q\,R$, R^2 and R. Consider some of the principal ratio cases.

For transmission lines possibly the ratios arising from equivalent R, X, G, B, and Z at either end may not appear particularly natural, but the principles here developed apply to all circuits including those of communication engineering, so that these conditions are of importance. In any case the ideas are fundamental.

Other ratios of importance are efficiency, regulation, and power factor. Efficiency is either x'/x or x/x' according to circumstances. Regulation is neither z'/z nor z/z' but is definitely associated with these numbers, so that the regulation is constant when z'/z is. Power factor is given by y/x at one end and y'/x' at the other. These are the tangents of the phase angle and hence fix the power factor by the cosine. By using the principles stated it is possible to obtain very easily some of the fundamental loci. These are in general circles and belong to the system defined by the numerator and the denominator as illustrated in the "kite" framework of Fig. 4.

Regulation index z'/z : Circles center A.

Efficiency index x'/x : $x = 0$ is radical axis of the system.

$x' = 0$ is shown with center C. The loci for variable efficiency are circles with this radical axis and one limit point at $\sqrt{p^2 - r^2}$ to the left of $x = 0$, that is at distance $\sqrt{a_{33}^2 - 1} \div (2\,a_{32})$.

R at A: This is x/w: Radical axis $x = 0$. Point circle $w = 0$. Loci are circles tangent to $x = 0$ at O.

X at A: This is y/w: Radical axis $y = 0$. Point circle $w = 0$. Loci are circles tangent to $y = 0$ at O.

G at A: This is x/z: $x = 0$ is infinite circle. $z = 0$ circle at infinity. Loci are lines parallel to $x = 0$ (as is evident).

B at A: this is y/z: $y = 0$ is infinite circle. Loci are lines parallel to it.

Z at A: this is z/w: Loci concentric circles around O.

R at B end: this is x'/w: Point circle $w' = 0$ is on circle $x' = 0$. Loci are circles, centers on $C B$ passing through B. $D B$ is a member.

G at B: this is x'/z': Loci are circles, centers on $C A$ passing through A. $A D$ is a member.

X at B: this is y'/w': Loci are circles, centers on $D B$ passing through B. $C B$ is a member.

B at B: this is y'/z': Loci are circles, centers on $D A$ passing through A. $C A$ is a member.

Z at B: this is z'/w': Loci with $A D$ as limit points and radical axis the perpendicular bisector of $A D$. This line also is a member.

This last diagram is the same as for lines of magnetic flux with A and B as parallel conductors.

Power factor at A given by $y/x = \tan\theta$. Loci are lines through O.

Power factor at B given by $y'/x' = \tan\theta$. Loci are arcs of the system through A and B. Relative phases of current and voltage at B are preserved by the directions of the tangents to these arcs at the point B.

20. Interconnection of algebraic and geometrical methods. It is not necessary to dwell on the fact that in practical problems according to circumstances one of these methods or the other may prove more convenient, nor that it is of advantage always to have methods as different as possible so as to make certain of the result by a check.

Section 17 I (B) Case $Q\,M_r$: One-conditioned maximum. Here the algebraic solution is by $M\,(2, 3) = 0$ and the graphical by finding the limit points. They agree because the matrix gives equations which describe the line of centers and three circles intersecting this line in the limit-points, one circle being sufficient to define them.

Section 17 I (C) Case $Q^2\,M_r$: Two-conditioned maximum. Here $D\,(2, 3, 4)\,q_1 = D\,(1, 3, 4)\,q_2$ is the equation of the circle intersecting S_{21}, S_3 and S_4 orthogonally. By dispensing with the maximum condition and using this determinantal equation with the other algebraic conditions or else this circle with the geometrical conditions the same result should be obtained.

21. Examples.

(a) The voltage at Paugan Falls being 225.2 kv. (line) what are the conditions there when the loss on the line is the minimum possible?

First consider as a general circuit problem detached from its special features. It is a case of $Q\,M_q$ in Section 17 I (B) and is therefore solved by $M\,(2, 1) = 0$.

Here $L_1 = z' = q_1$ and $L_2 = x' - x$ is to be minimum.

Then $M\,(2, 1) = 0$ means

$$\begin{bmatrix} 1, & 0, & 0, & 0, \\ -\,b_{31} & -\,b_{32} & (1 - b_{33}) & -\,b_{34} \\ w' & z' & -\,2\,x' & -2\,y' \end{bmatrix} = 0$$

That is

$$z' \div (-\,b_{32}) = -\,2\,x' \div (1 - b_{33}) = 2\,y' \div b_{34}$$

or $\quad z' \div a_{13} = x' \div (a_{33} - 1) = y' \div a_{43}$

is the solution of the *general circuit problem*. For the *problem proposed* $q_1 = 1.69$.

Hence

$x' = 0.001001$ or 10.01 kw. $y' = 0.431$ or 4310 kv-a.

$w' = 0.1122$ or 1122 amperes-squared that is 33.5 amperes.

The power factor would be 0.0023 (leading).

This problem might have been considered as determined by the center of the circle $x' - x = 0$, or $R\,\overline{w} + G\,\bar{z} = 0$. As is evident from the latter form it is an imaginary circle but has a real center.

(b) The voltage being 225.2 on the same line at the S-end and the power factor at the R-end being 0.85 (lagging) find the maximum power that can be delivered.

As a general circuit problem this may be put in the form

$L_1 = z' = q_1$, $L_2 = x$, $L_3 = y$, where $y/x = \tan\theta$ and $L_4 = L_2$ to be maximum, a case of $Q\,R\,M_q$ of Sec. 17 I (C). The determinantal condition simplifies to $D\,(1, 2, 3) = 0$ that is

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ w & z & -\,2\,x & -\,2\,y \end{vmatrix} = 0$$

this reduces to $w = z\,a_{11} \div a_{12}$. Let $a_{11} \div a_{12} = c^2$

Then

$u^2 + v^2 = c^2$, $v/u = \tan\theta$, hence $u = c\cos\theta$, $v = c\sin\theta$

Then $\quad z = q_1 \div S_1$ where

$$S_1 = 2\,a_{11} + c\,a_{13}\cos\theta + c\,a_{14}\sin\theta$$

Thus $\quad x = u\,z = q_1\,c\cos\theta \div S_1$

$$y = v\,z = q_1\,c\sin\theta \div S_1$$

In the special values of this problem $q_1 = 1.69$, $\cos\theta = 0.85$ hence $\sin\theta = -\,0.52679$.

Then

$x = 5.1125$ or 51125 kw. $y = -\,3.169$ or 31690 kv-a. (lagging)

$z = 0.4924$ corresponding to 121.5 kv. line volts.

In both this and the preceding example the results as worked out are for one phase both as to current and voltage, the data however are supposed given for line voltage.

22. In conclusion the author wishes to thank Mr. V. G. Smith and Mr. G. de B. Robinson for assistance in the preparation of this paper.

Discussion

V. G. Smith: It will be noticed that Professor Rosebrugh uses $\mathbf{I}\hat{\mathbf{E}} = P + jQ$ throughout. This makes Q positive for leading power factors. It is to be hoped that this definition will be adopted as it makes the power diagrams similar to the usual vector diagrams.

In using this work it should be remembered that while z, w, x, y and z', w', x', y' are defined as the received and transmitted quantities respectively the definition is algebraic. Negative power received is positive power transmitted and vice versa. Similarly for the reactive volt-amperes.

functions. The position of the center and the radius is obvious in each case from the equation. A similar set of diagrams for the transmitting end may be determined in the same manner.

It will be noticed that either the voltage or the current is assumed known. Usually the voltage will be known which makes the first three diagrams the most useful. A particular problem, however, may call for any one of the six as the best means of attack.

By considering the diagrams as vector diagrams with loci placed upon them, the phase relations as well as magnitudes are seen, which is a great convenience.

T. R. Rosebrugh: Mr. V. G. Smith has raised a question of

TABLE I

$L = az + bw + cx + dy$ or $L_1 - kL_2 = 0$ which is $L = 0$

Vector basis	Where	Equation of the circular locus for constant L and z or w	Name of the diagram
$\frac{\mathbf{E}_1}{\mathbf{B}\,\mathbf{E}_o} = \frac{\mathbf{A}}{\mathbf{B}} + \mathbf{Y}_o$ $\frac{\mathbf{I}_1}{\mathbf{D}\,\mathbf{E}_o} = \frac{\mathbf{C}}{\mathbf{D}} + \mathbf{Y}_o$	$\mathbf{Y}_o = \frac{\mathbf{I}_o}{\mathbf{E}_o}$ $\mathbf{Y}_o = G_o + jB_o$	$\left(G_o + \frac{c}{2b}\right)^2 + \left(B_o + \frac{d}{2b}\right)^2 = \frac{L}{bz} + \frac{c^2 + d^2 - 4ab}{4b^2}$	Admittance or Shand or Evans and Sels modified
$\frac{\mathbf{E}_1}{\mathbf{B}} = \frac{\mathbf{A}}{\mathbf{B}}\mathbf{E}_o + \mathbf{I}_o$ $\frac{\mathbf{I}_1}{\mathbf{D}} = \frac{\mathbf{C}}{\mathbf{D}}\mathbf{E}_o + \mathbf{I}_o$	$\mathbf{I}_o = I_a + jI_r$	$\left(I_a + \frac{c\sqrt{z}}{2b}\right)^2 + \left(I_r + \frac{d\sqrt{z}}{2b}\right)^2 = \frac{L}{b} + \frac{c^2 + d^2 - 4ab}{4b^2}z$	Current
$\frac{\mathbf{E}_1\hat{\mathbf{E}}_o}{\mathbf{B}} = \frac{\mathbf{A}}{\mathbf{B}}\mathbf{E}_o^2 + P_o + jQ_o$ $\frac{\mathbf{I}_1\mathbf{E}_o}{\mathbf{D}} = \frac{\mathbf{C}}{\mathbf{D}}\mathbf{E}_o^2 + P_o + jQ_o$	$\mathbf{I}_o\hat{\mathbf{E}}_o = P_o + jQ$	$\left(P_o + \frac{cz}{2b}\right)^2 + \left(Q_o + \frac{dz}{2b}\right)^2 = \frac{L}{b}z + \frac{c^2 + d^2 - 4ab}{4b^2}z^2$	Volt-ampere or Evans and Sels
$\frac{\mathbf{E}_1}{\mathbf{A}\,\mathbf{I}_o} = \frac{\mathbf{B}}{\mathbf{A}} + \mathbf{Z}_o$ $\frac{\mathbf{I}_1}{\mathbf{C}\,\mathbf{I}_o} = \frac{\mathbf{D}}{\mathbf{C}} + \mathbf{Z}_o$	$\mathbf{Z}_o = \frac{\mathbf{E}_o}{\mathbf{I}_o}$ $\mathbf{Z}_o = R_o + jX_o$	$\left(R_o + \frac{c}{2a}\right)^2 + \left(X_o + \frac{d}{2a}\right)^2 = \frac{L}{aw} + \frac{c^2 + d^2 - 4ab}{4a^2}$	Impedance
$\frac{\mathbf{E}_1}{\mathbf{A}} = \frac{\mathbf{B}}{\mathbf{A}}\mathbf{I}_o + \mathbf{E}_o$ $\frac{\mathbf{I}_1}{\mathbf{C}} = \frac{\mathbf{D}}{\mathbf{C}}\mathbf{I}_o + \mathbf{E}_o$	$\mathbf{E}_o = E_a + jE_r$	$\left(E_a + \frac{c\sqrt{w}}{2a}\right)^2 + \left(E_r + \frac{d\sqrt{w}}{2a}\right)^2 = \frac{L}{a} + \frac{c^2 + d^2 - 4ab}{4a^2}w$	Voltage
$\frac{\hat{\mathbf{E}}_1\mathbf{I}_o}{\hat{\mathbf{A}}} = \frac{\hat{\mathbf{B}}}{\hat{\mathbf{A}}}I_o^2 + P_o + jQ_o$ $\frac{\hat{\mathbf{I}}_1\mathbf{I}_o}{\hat{\mathbf{C}}} = \frac{\hat{\mathbf{D}}}{\hat{\mathbf{C}}}\mathbf{I}_o^2 + P_o + jQ_o$	$\hat{\mathbf{E}}_o\mathbf{I}_o = P_o + jQ_o$	$\left(P_o + \frac{cw}{2a}\right)^2 + \left(Q_o + \frac{dw}{2a}\right)^2 = \frac{L}{a}w + \frac{c^2 + d^2 - 4ab}{4a^2}w^2$	Volt-ampere

Six vector diagrams and the equations for determining circular loci on them for a constant value of any linear function of the four quantities z, w, x, y

Mr. L. A. Paine has invented the name of "Quads" for reactive volt-amperes. The name seems apt as it comes from the conception of quadrature power and has Q for its initial letter.

Professor Rosebrugh has confined his diagrams to the admittance (u, v) plane. There is a number of real quantity diagrams and all of them have a vector meaning which should be kept in mind.

Table I shows the vector basis of six diagrams which have an obvious electrical meaning and the equation of the circular locus for a constant value of any linear function of the four quantities z, w, x, y or a constant value of the ratio of any two linear

standardization of meaning of terms. Besides the definition of positive sense for Q and of a short name for the quantity to which he refers, there is a number of other instances. There are the four "general circuit constants," as in the equations (1), the sixteen coefficients of equations (12) and the inverse set of equations (14). In view of their number it would not appear desirable to attempt to assign individual names to these 32 coefficients but to leave them to be designated by a symbol with standard subscripts as here.

Each set of sixteen coefficients consists in fact of six absolute ratios, four impedances, four admittances, two of the nature of

impedance-squared and two of admittance-squared. But the four "general circuit constants" might very well have characteristic names given to them instead of calling them by letters.

It might be suggested that *voltage-transformance* and *current-transformance* would suitably describe the first and the fourth general circuit constants, while another name of the resistance class such as *obstructance* would do for the second and perhaps *percolance* (suggesting conductance) would do for the third.

Mr. Smith has made a substantial contribution to the value of the paper by his analysis of the possible diagrams having simultaneously vector and real quantity interpretations. The analytical portion of my paper would of course apply equally, however the data might be represented graphically. While the interconnection of graphics and analysis as treated in the paper is worked out solely for the first diagram of Mr. Smith's table, there would also be formal agreement of a similar kind in the case of the fourth of his list. The situation would be different for the other diagrams but these I have not considered.

Study of the Effect of Short Lengths of Cable on Traveling Waves

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Member, A. I. E. E. Associate, A. I. E. E. Member, A. I. E. E.

Synopsis.—Cathode ray oscillographic tests were made of traveling waves passing from an overhead line into short lengths of cable. Single-phase cable lengths of 500 and 1000 ft. were used. Tests were made with a wide variety of conditions, such as cable at end of line, cable between two sections of line, etc. The tests demonstrated that a short length of cable does not act as an effective protective device when connected between station and incoming line. When the traveling wave on the incoming line has a long flat top, several times the cable length, the crest of the wave passing the cable is decreased only a few per cent by the presence of the cable, although the wave-front is sloped off if it was originally very steep. When the wavelength is approximately the same as the cable length, the cable can reduce the transient voltage to less than half of the value without the cable. Recent measurements on transmission lines show that waves do occur with approximately flat tops which are several thousand feet in length. Therefore the cables do not permit the omission of lightning arresters which are means of reducing the potential of overvoltage surges. This confirms the theoretical calculations and the practise of using lightning arresters with cables.

The resistance of the ground connection of the cable sheath was found to have important effects. With the cable sheath at the end grounded through 28 ohms, a potential of 82 kv. was measured at the sheath and 105 kv. at the cable conductor.

The protective action of lightning arresters was demonstrated by using a gap and various values of series resistance.

The velocity of propagation in the cable was found to be about 61 per cent of the velocity of light. The surge impedance of the cable was determined by several methods. Calculations based on the measured propagation velocity and measured capacitance in accordance with the formula

$$Z = \frac{1}{C\,v}$$

gave a value of about 50 ohms. Some of the other methods gave values of about 100 ohms.

* * * * *

THERE has been much discussion for many years concerning the effectiveness of cable in reducing the potential of incoming surges, and as a result considerable uncertainty has existed as to whether or not current practises are correct with regard to methods of protection, both of the cable itself and of apparatus connected to the cable.

Recognizing this problem as being of great importance to both manufacturers and operators, a joint investigation by the General Electric Company, the Consumers Power Company, and the Detroit Edison Company was arranged late in the summer of 1929.

The General Electric Company furnished a portable impulse generator and sphere-gaps for measuring voltage. The Consumers Power Company supplied the S-19 transmission line, a portable power supply, communication and trucking facilities. The Detroit Edison Company furnished 1000 ft. of 24,000-volt lead sheath cable and a portable cathode ray oscillograph.

The tests were conducted at Croton Dam, Michigan, between August 26, 1929 and November 7, 1929.

The tests dealt with the following subjects:

1. Free waves on the transmission line.
2. Effect of 500 ft. of cable.
3. Effect of 1000 ft. of cable.
4. Effect of bus between two sections of cable, each 500 ft. long.
5. Effect of terminal conditions with 500 ft. of cable.
6. Effect of terminal conditions with 1000 ft. of cable.
7. Effect of grounds on sheath of the cable.
8. Effect of lightning arrester—gap setting and resistance.
9. Effect of lightning arrester—on the wave, on the line, and with bus between two sections of cable.

Impulse Generator. The portable impulse generator[1] used in these tests consisted of 40 banks of capacitors each having a capacity of 0.5 μf. The banks were charged in parallel to 20 kv. each and discharged in series according to the well known Marx circuit. During most of these tests the potential of the generator was reduced by disconnecting part of the banks to prevent breakdown of the cable or arcing over the potheads.

Transmission Line. The transmission line used for the tests was a section of the S-19 line of the Consumers Power Company, a description of which has already been published.[2] The location of the cable for the tests was at towers 53 to 55, a distance of 5.16 to 5.36 miles from the impulse generator which was at the Croton end of the line. The main impulse was sent out on the middle conductor and the bottom conductor was used to carry an initiating impulse.

Strain insulators were installed on towers 53, 54, and 55 to enable a section of the cable to be inserted between sections of the line.

Oscillograph. The oscillograph used for measuring the wave-shapes was of the hot cathode type described by George.[3] The oscillograph and its auxiliaries were easily portable, being mounted on a truck. (See Fig. 1.)

Cable. The cable used for these tests consisted of 1000 ft. of lead sheath cable having 21/32-in. manila

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

1. For references see Bibliography.

paper insulation, and a single conductor consisting of a number 00 seventeen-strand copper. The capacity of the cable as measured with a capacity bridge was 0.03734 μf. per 1000 ft. The voltage rating of the cable was 24,000 volts.

The potheads at the cable terminals were the type used by the Detroit Edison Company, and were installed by their cable men.

Sphere-Gaps. Several sizes of sphere-gaps, ranging from 2.5 cm. to 25 cm. diameter were used to measure crest voltage.

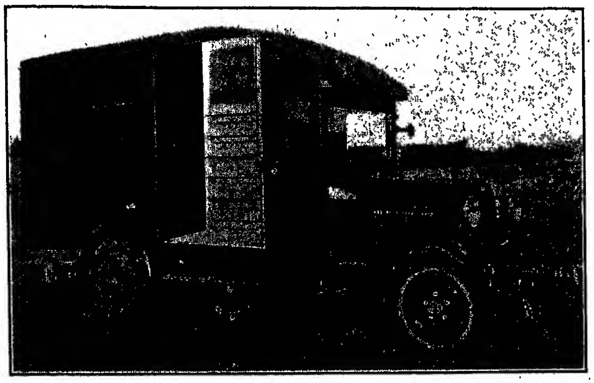


Fig. 1—Illustration of Impulse Generator Truck

Methods

Cable Divider. A cable divider similar to the one which was described by Gabor[4] was used to reduce the voltage to a safe value for use on the deflecting plates of the oscillograph. By using the cable divider, it was possible to make measurements at each end of the cable without moving the oscillograph, which was a decided advantage.

The cable divider consisted of a section of *B X* cable No. 14 double conductor 500 ft. in length. One conductor was tied to the sheath and grounded at each end. The other conductor was used to conduct the transient to the deflecting plates of the oscillograph. At the oscillograph end of the *B X* cable a resistance equal to the surge impedance of the cable was placed to ground. At the other end of the cable a high resistance was placed from the conductor to the point where the transient was to be measured. The ratio between the resistances at the two ends of the cable is the ratio of the voltage division. After making a number of comparative tests with the cable divider and capacity divider, the conclusion was reached that the cable divider reproduced the transient with sufficient accuracy, and that it was dependable in its operation. In Gabor's description of the cable divider, there was a capacity at each end of the cable. These capacities are used to suppress the 60-cycle current in the measuring circuit, but were not necessary in these tests since there was no 60-cycle voltage on the line. However, check tests were made using capacities. It was necessary to check the high-resistance water tube at the line end of the measuring cable at frequent intervals to prevent changes in the ratio due to temperature.

Determination of Time Scales and Sweeping Speeds. In order to eliminate any doubt as to timing, a 500-kilocycle wave was superimposed on one measured wave for each condition tested. The frequency of the oscillator was checked with a precision wave meter. This method gives a check on the sweeping speed of the oscillograph, and a time scale for the transient. Usually the transients were taken, one with 500 kilocycle superimposed, and one without, to give a continuous check on the calibration which changes somewhat with changes in vacuum. Many oscillograms in this paper show the 500-kilocycle superimposed wave.

Sphere-Gap Measurements. Sphere-gap measurements were taken for each test condition to give the crest value of the voltage. Because dirty gaps are apt to be erratic, the gaps were cleaned at frequent intervals.

Operation of the Oscillograph and Impulse Generator. Fig. 2 is a schematic diagram showing the operation of the circuits which were used with the oscillograph. The transients waves were sent out at scheduled intervals by an operator at the impulse generator station, who closed a switch in the initiating circuit. The initiating circuit was arranged to send a 20-kv. impulse out on the line (bottom conductor) and to start the main impulse of the generator (middle conductor). There was a short delay between the 20-kv. initiating impulse and the main impulse which depended upon the time constant of the circuit coupling the two impulse circuits.

At the oscillograph the shutter was opened and the circuits energized before the main transient was due. The 20-kv. initiating impulse arriving before the main transient, tripped a three-electrode gap, thus starting oscillations in a local circuit. The grids of the tubes in the sweeping and electron gun circuits were coupled to the oscillating circuit so that they became energized when the local circuit began oscillating. The electron gun circuit turned on the beam and the sweep circuit

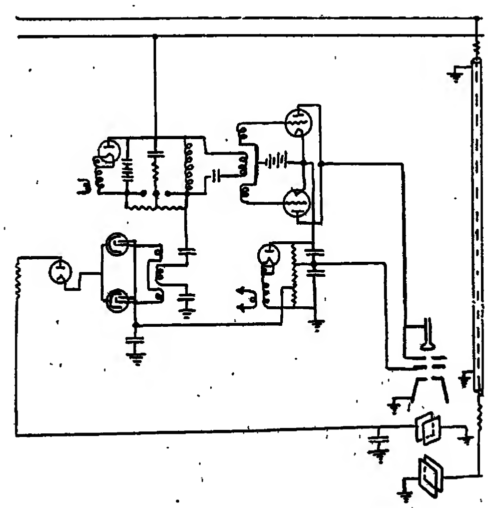


Fig. 2—Circuit Diagram

moved the beam across the film giving the time scale. The time interval between the arrival of the 20-kv. initiating impulse and the main impulse was made such that the deflection due to the main transient began after the beam had moved a short distance along the zero line. This made it possible to record the start of the transient under investigation.

Test Wave Forms. At different times as many as five different waves were used. The form of these different waves is given in Table I. All the waves used were of negative polarity.

TABLE I
DATA ON WAVE FORMS USED

Designation	Voltage crest at Tower 53	Time to reach crest ms.	Time to decay to 50% crest ms.	No. of generator banks used	Series inductance henrys
Steep wave low voltage.	92	8	50	7	0
Medium wave low voltage................	120	13-15	40	10	0.002
Slow wave low voltage..	124	27	50	14	0.011
Steep wave high voltage	225	8	15	32	0
Medium wave high voltage.................	223	10	20	32	0.002

Preliminary Measurements

Surge Impedance of the Line. Surge impedance measurements were made by connecting a water tube of varying resistance from line to ground and measuring the $I\,R$ drop across the water tube and the voltage from the line to true ground.* Measurements were made both with the line continuous and line open.

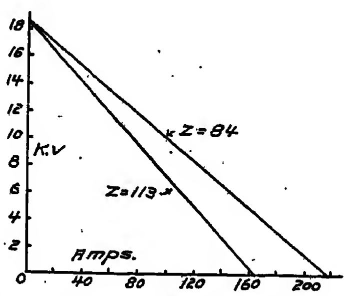


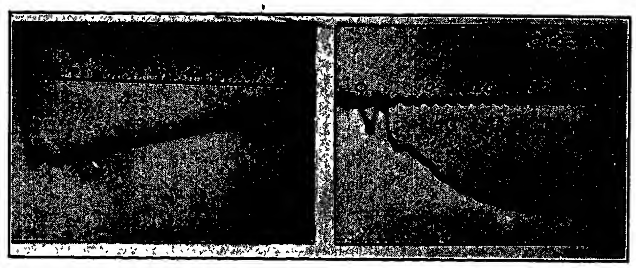
Fig. 3—Surge Impedance Measurement on 1000 Ft. Cable

By this method the value for surge impedance of the middle conductor of the S-19 line used in these tests was found to be from 595 to 685 ohms. The measurements which are considered most reliable are 610 and 624 ohms. A value of 620 ohms was chosen for purposes of calculation.

Surge Impedance of the Cable. The surge impedance of the cable was determined by several methods. Each method will be described briefly and the results summarized.

The first method was similar to that used for surge impedance measurements on the transmission line. The steep wave was used and was chopped by a gap at Tower 48 which was considered to be far enough away so that reflections would not affect the result. The success of this method depends on the wave being short enough so that reflections between the two ends of the cable do not affect the measurements. In general the space wave in the cable should be less than twice the cable length although a longer wave might give the same results depending on the shape of the tail. Fig. 3 shows two values obtained, 84 and 113 ohms.

The second method is based on the reduction of voltage which occurs when a steep wave enters the cable. In Fig. 4 are shown two oscillograms, taken at Tower 53, one with the line continuous and the other with 1000 ft. of cable in circuit, but with the far end of the cable open. The effect of the cable was to reduce the wave from 92 kv. to 30 kv. on the first reflection. This was subsequently increased by successive reflections. The surge impedance of the line was determined by previous tests to be about 620 ohms. Then the surge impedance of the cable was calculated from the formula $Z_c' = E_t\,Z_1\,2/E_o - E_t = 121$ ohms. This value of surge impedance may be considered as consisting of the actual surge impedance of the cable plus the resistance between the sheath and ground at the start, which in this case is 28 ohms. Subtracting: $Z_c = Z_c' - 28 = 93$ ohms.



Wave on continuous line at Tower 53 | Wave entering 1000-ft. cable at Tower 53

Fig. 4—Oscillograms of Effect of 1000-Ft. Cable on Traveling Wave

The second method was also applied to measurements at the far end of the cable using sphere-gap values. It was unnecessary to take oscillograms for this case because the chopped wave which was used was short compared to the cable length, so there was no building up of the voltage by successive reflections. The values obtained by this method were 38 to 54 ohms. These values are probably too low due to attenuation of the voltage through the cable, and to difficulty of measuring accurately such a short wave with sphere-gaps.

The third method was to calculate the surge impedance by using the measured propagation velocity of the wave through the cable and the measured capacity in the formula: $Z = 1/(C\,v)$. The propagation velocity was calculated from the reflections on film C-20-8, Plate VI, and was found to be 61.2 per cent of the velocity of light. The capacity of the cable as measured

*This method is described in greater detail in Reference 2.

by a bridge was 0.0373 μf. The surge impedance calculated by this method is 44.5 ohms.

In the fourth method the impedance was calculated from the geometrical constants of the cable, which were as follows:

Diameter of conductor (No. 00).............0.413 in.
Thickness of insulation.....................0.656 in.
Dielectric constant (assumed)...............3.0

Applying the usual formulas to these constants gives a surge impedance of 47.3 ohms.

Summary of Results on Surge Impedance

Method	Z in Ohms
Varying terminal impedance	84 to 113
Transmitted wave, sphere-gap measured far end	38 to 54
Transmitted wave oscillogram, near end	93
Calculated based on propagation velocity	44.5
Calculated based on geometrical constants	47.3

These figures for the surge impedance seem to fall into two groups, one about 50, and the other approximately 100 ohms. It is believed that this discrepancy is not due entirely to errors in taking the data, but rather to factors which are not considered.

Results of Tests

The results of the tests are shown in a series of plates on which the oscillograms dealing with each of the subjects studied are grouped. Each of the plates will be discussed separately, and a summary of results given at the end of the paper. On some of the plates oscillograms are repeated from other plates so that those on any one plate are complete and comparable. In all tests with the cable the sheath was grounded at both ends unless otherwise specified.

Plate I. Shape of the Waves and Effect of Distance

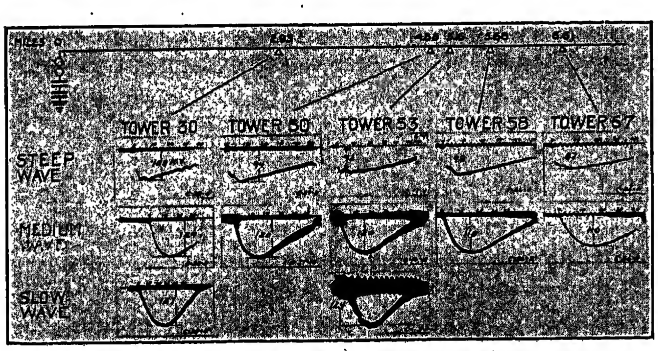


Plate I. Shape of the Waves and Effect of Distance Traveled

Traveled. The oscillograms on Plate I show the time voltage characteristics of the three waves used during the tests as recorded by the oscillograph at several locations on the line. These curves represent free traveling waves on the line and were recorded with a continuous line from the lightning generator at Croton to the Wealthy Street Plant at Grand Rapids. No equipment other than measuring apparatus was connected to the line at the time the tests were made.

Steep Wave. From the oscillograms, Plate I, it can be seen that the voltage was reduced from 103 kv. at Tower 30 to 87 kv. at Tower 67, a reduction of 14.7 per cent in 3.7 miles. The wave is made up of a very sudden rise at the start, followed by a slower rise having imposed on it an oscillation which continues until crest value is reached. After crest value, the voltage reduces along a smooth curve reaching 50 per cent of crest value in about 50 microseconds. It may be noted that the recorded wave-front is somewhat different at the various

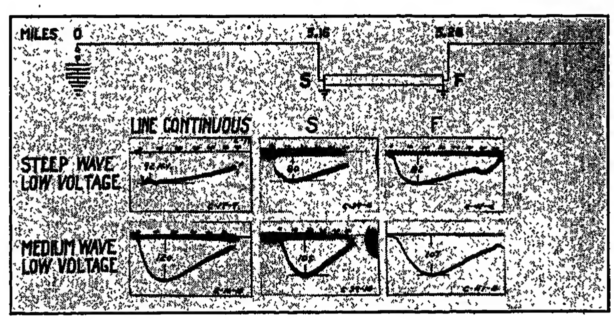


Plate II. Wave Passing Through 500 Ft. of Cable

tower positions, possibly due to differences in phase relation between the fundamental wave-shape and an oscillation on the front. On the waves recorded at Towers 30 and 53, the oscillation and the fundamental appear to add together in such a manner that the initial rise of voltage is almost equal to the crest value. The oscillation apparently attenuates rapidly and is of low magnitude at Tower 67.

Measuring equipment connected to the line apparently caused a partial reflection which goes back to the generator and returns, producing the sudden rise in voltage on the tail of the waves recorded at Towers 30, 50, and 53. The time at which this rise is recorded in each case checks the calculated time for the travel of a wave from the measuring apparatus to the generator and back again.

Medium Wave. The medium wave reduces from a value of 129 kv. at Tower 30, to 110 kv. at Tower 67, a reduction of 15 per cent. This is about the same reduction as was noted with the steep wave.

The medium wave consists of a smooth rise in voltage from zero to crest value in from 13 to 15 microseconds followed by a gradual decrease to half voltage in approximately 40 microseconds. This wave can be represented very closely by the equation: $e = 240\ \epsilon^{-0.033t} - \epsilon^{-0.134t}$ where e is in kilovolts and t in microseconds. Comparison of oscillograms made at various locations (Plate I) show no perceptible change in wave-shape due to travel along the line.

Slow Wave. The slow wave is smooth throughout and reaches a crest value at approximately 27 microseconds and decreases to 50 per cent crest voltage at 50 microseconds as indicated by the oscillogram taken at Tower 30. (The time scale of oscillogram C-9-2 is not reliable.) The crest voltage is 124 kv. at Tower 53.

Plate II. Wave Passing Through 500 Ft. of Cable.

When the wave enters a 500-ft. section of cable, the oscillograms show that the time for the voltage to rise to its crest value with the steep wave (8-microsecond front) was 12 to 15 microseconds. The crest voltage was reduced from 92 to 80 kv. or about 12 per cent. The amount of reduction depends principally on the shape of the tail of the incident wave. If the voltage drops rapidly, it will limit the voltage which can be built up in the cable. The wave-front of the medium wave was slow enough so that the cable did

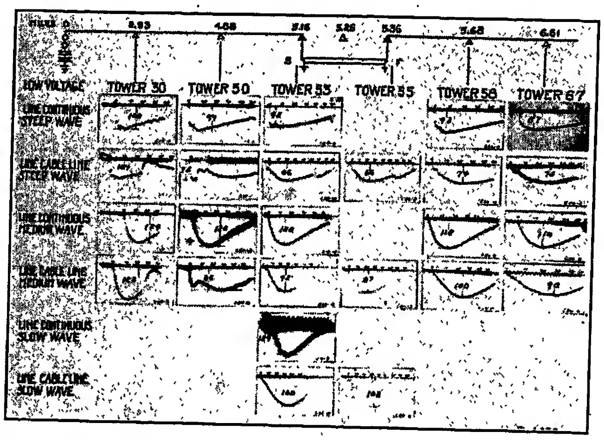


Plate III. Wave Passing Through 1000 Ft. of Cable

not have any effect on its shape, although the potential was reduced from 120 kv. to 105 kv.

Plate III. Wave Passing Through 1000 Ft. of Cable. When a 1000-ft. section of cable was inserted into the line the crest voltage was reduced from 92 kv. on the free line to 70 kv. for the steep wave with the cable inserted, a reduction of 24 per cent. The wave front was changed from 8 microseconds on the free line to 22 microseconds.

In the case of the medium wave the crest value was reduced from 120 kv. to 92 kv., a reduction of 23.3 per cent. The wave-front was changed from 15 microseconds to 25 microseconds.

The reduction in crest value of the slow wave was from 124 kv. to 102 kv., a reduction of 18 per cent.

The oscillograms taken at Towers 30 and 50 (Plate III) show the effect of the reflection from the cable on the incident wave. Of course as the oscillograph location approaches the end of the cable the reflections approach the front of the incoming wave. Oscillogram C-29-2, taken at Tower 30, shows the reflection returning from the cable about 24 microseconds from the beginning of the incident wave.

The magnitude of the reflected wave is about 50 kv. At Tower 50 the reflected wave is nearer the crest of the incident wave.

The medium and slow waves show reflections which are similar to those of the steep wave.

Wave-Shape on Line Beyond Cable. There was no distinguishable change in wave-shape along the line after the wave passed through the cable. The oscillograms taken beyond the cable at Towers 55, 58, and 67 are similar for the three waves. The rate at which the voltage builds up in the cable by successive reflections is shown most clearly by oscillogram C-25-15 at Tower 58.

Plate IV. Effect of Bus Between Cable Sections. For the steep wave low-voltage condition, a comparison of the two cases where a 1000-ft. section or two 500-ft. sections is inserted in the line, shows that with the incident wave of 92 kv. and a front of 8 microseconds, the 1000-ft. section reduces the crest voltage to 66 kv., while with the two 500-ft. sections, the crest is 71 kv. For this test the two 500-ft. sections of cable were connected together by a short jumper about 20 ft. in length. In general, the 1000-ft. section and the two 500-ft. sections have practically the same influence on the wave. The only apparent difference in the shape of the two waves is in the oscillations which appear at the front of the wave (C-40-2 and C-46-18).

Oscillogram C-41-4 which shows the wave-shape at the junction of the two cable sections, indicates that voltage conditions at this point are almost identical with the conditions at the ends of the combined sections. As may be noted, the wave at the start of the cable is practically identical with the wave at the finish of the cable on both the 1000-ft. and the two 500-ft. cable sections.

The third group of oscillograms on Plate IV were taken with a set-up consisting of two 500-ft. sections of cable connected together through a 500-ft. section of

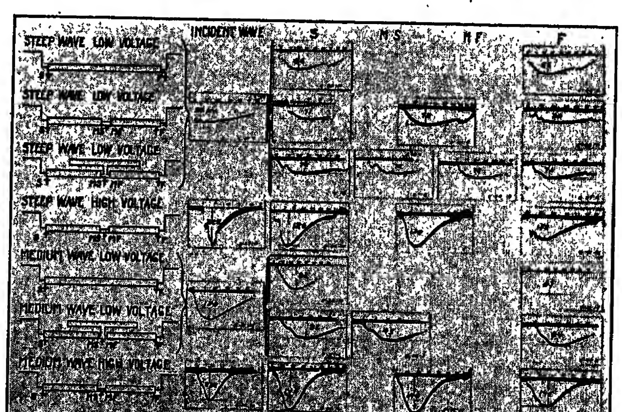


Plate IV. Effect of Bus Between Cable Sections

overhead line to simulate a station bus. The shape of the wave was altered at each end of the first section of cable by reflections from the second section which cut into the front of the wave and caused it to drop momentarily.

The crest values of voltage 70 to 72 kv. measured at the four positions with two sections of cable and a section of bus between, have approximately the same value at all of the positions. This value of crest voltage is practically the same as that for the 1000-ft. length, which is 66 to 70 kv.

Steep Wave High Voltage. The results in this case were similar to the ones discussed for the steep wave, low-voltage. When high voltages were applied to two 500-ft. sections of cable the oscillograms showed essentially the same magnitude and wave-shape at the start, the junction, and the finish of the two cable sections. The principal difference in the wave-shape at these points was a variation in the phase relations between the fundamental and an oscillation which appears on the wave-front.

By inserting the 1000-ft. length of cable in the line, the crest voltage was reduced from 225 kv. to 120 kv.,

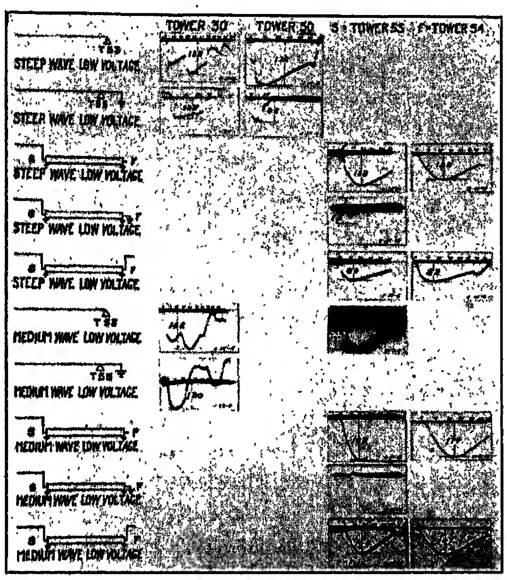


PLATE V. EFFECT OF TERMINAL CONDITIONS

which is 53 per cent. The wave-front also was changed from 8 microseconds to 15 microseconds. This case is to be compared with the steep wave low-voltage case. It will be noted that the change occurring in the wave-front is slightly different for the two cases. In the case of the high-voltage wave, the section at approximately crest value is very short, and the decay is very rapid. As a result, the incident voltage begins to drop before the voltage in the cable has had sufficient time to build up to its ultimate value. The low-voltage wave had a much longer duration at approximately crest value. Hence the voltage in the cable has a longer time to build up to its crest value before the incident wave begins its rapid decay. For this reason the reduction in crest voltage was greater for the high-voltage wave than for the low-voltage wave.

Medium Wave, Low Voltage. The bus between the cable sections had the same general effect as was found with the steep wave, although the reflections were not as pronounced. The relations between crest voltages at the various points were similar to those found on the steep wave tests.

Medium Wave, High Voltage. When the medium wave, high voltage was applied to the two sections of cable with no bus between, the wave-front of the resultant wave had an 18-microsecond front as compared with 10 microseconds for the incident wave. The crest voltage was reduced from 233 kv. to 146 kv., a reduction of 37.2 per cent.

Plate V. Effect of Terminal Conditions. In Plate V oscillograms are shown for a variety of terminal conditions, with and without the 500-ft. length of cable in circuit.

With line open and with it connected to ground the reflections both with the steep wave and with the medium wave are clearly defined. With the line open the reflection adds, while with the line closed to ground the reflection subtracts.

Ground at "F." The ground at F on the cable conductor holds the voltage at both ends to a low value. With the steep wave, the initial rise in voltage (13 kv.) and two reflections were measured.

Line to Cable to Line, and Line to Cable (Low Voltage). Comparing the conditions where a line is open to the case where the line is connected to a cable, the far end of the cable being open, we find that the cable has reduced the crest voltage from 170 kv. to 132 kv., a reduction of 22.3 per cent. By having the cable inserted between two sections of line the voltage is reduced to 80 kv.

The medium wave tests show the voltage of the line-cable condition 70 per cent higher than that of the line-cable-line condition. Oscillogram C-39-12 shows a chopped wave resulting from an accidental arc-over of one of the leads to the cable pot-head.

Plate VI. Terminal Conditions with 1000-Ft. Cable. Oscillogram C-28-18 with the steep wave shows the incident wave and the reflections at Tower 30, which was about 2.3 miles from the start of the cable. For

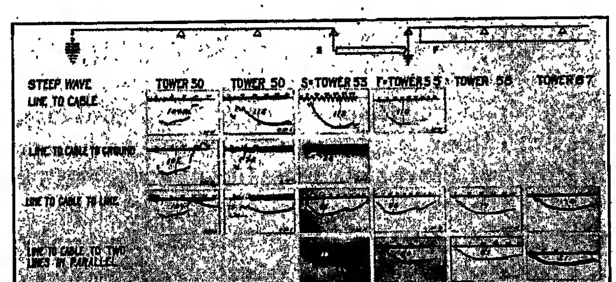


PLATE VI. TERMINAL CONDITIONS WITH 1000 FT. CABLE

the first 25-microseconds the wave was unaffected by reflections and corresponds to the incident wave. At 25 microseconds a negative reflection with respect to the incident wave comes back as a result of the incident wave passing into the cable which is of lower surge impedance than that of the line. The voltage then remains almost constant for about 3 microseconds, which represents the time required for the wave to pass through the cable and be reflected to double voltage. The sudden rise in voltage at 33 microseconds is due to the first reflection from the far end of the cable. The

voltage then continues to rise by steps as the wave reflects back and forth in the cable, approaching its maximum value. The second of this series of steps occurs at 37 microseconds. The oscillograms taken at Towers 50, 53, and 55 show the same effect as that shown in the oscillograms previously discussed, the only difference being in the time relation between the incident wave and the reflections.

It may be seen that the voltage at the far end of the cable for the line-cable condition was 110 kv. or 120 per cent of the incident wave, which was 92 kv., as seen from Plate I. The voltage did not rise to twice the value of the incident wave because the incident wave was of relatively short length. The decay of voltage on the tail of the wave was at approximately the same rate as the build-up of voltage through the cable.

The medium wave and the slow wave which are reproduced here showed similar behavior except that the reflections are not as well defined.

Line to Cable to Line. The oscillograms shown in the

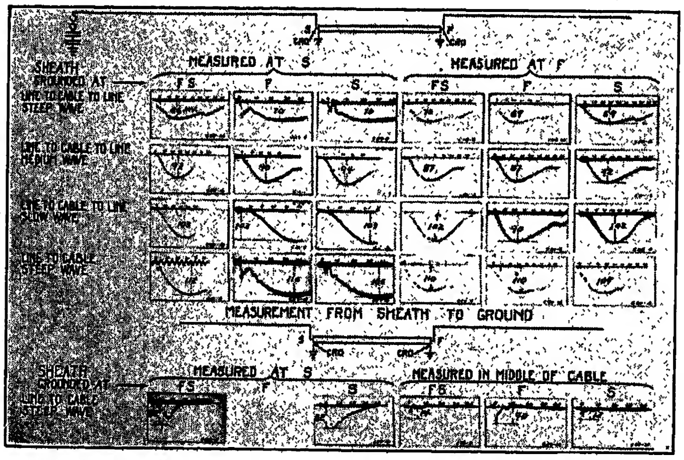


PLATE VII. EFFECT OF GROUNDS ON CABLE SHEATH

line-cable-line condition are similar to those discussed in the line-cable condition except that the reflections at the far end of the cable are less, due to the fact that a portion of the wave is transmitted onto the line. This results in a decrease in voltage as may be seen by a comparison of the line to cable and line-cable-line conditions at Tower 55 (steep wave) which shows the voltage to be 110 kv. for the line-cable condition as compared to 66-70 kv. for the line-cable-line condition, a reduction of 40 per cent. Comparison of corresponding oscillograms for the medium and slow waves shows similar behavior, the reduction being 40 per cent for the medium wave, and 39 per cent for the slow wave.

Waves measured at Towers 58 and 67, beyond the cable, give essentially the same wave-shapes as those at the far end of the cable.

It may be seen at the start end of the cable that the steep wave reaches its crest in 25 to 30 microseconds for the line-cable line condition.

Line to Cable to Ground. Waves recorded for the line to cable to ground condition are identical to those of the line to cable condition up to the time of the first reflection from the far end of the cable. This reflection comes back negative (with respect to the incident wave) instead of positive. The result was an oscillation in the cable as is shown on oscillogram C-24-3. The first rise in voltage goes to 26 kv. followed by seven reflections which are readable on the original film.

Line to Cable to Two Lines in Parallel. The difference in shape of the wave with two lines in parallel when compared to one line, is too small to be detected on the oscillograms. The voltage was lowered from 70 to 60 kv. (Plate VI) which is a reduction of 14 per cent when measured at F.

Plate VII. Effect of Grounds on Cable Sheath. Voltage Between Conductor and Ground. The only condition where the variation in the grounding of the sheath had any effect was with the steep wave, line-cable-line and line-cable conditions. Grounding at the start of the cable only, gave the same result as grounds at both the start and finish of the cable, whereas grounding at the finish only gave a much higher initial rise in the voltage at the beginning of the wave. The final wave-shape was the same as in the other conditions of grounding.

Sheath to Ground Voltage. With the sheath grounded at F and S or at S only, the initial voltage rise on the sheath measured at S was practically the same when a steep wave was used. The tail of the wave was lower and the voltage dropped faster with both ends grounded than with a ground at S only. This was due to the lower resistance of the two cable sheath grounds in parallel. The voltage which appears at S, when S is grounded, is due to ground resistance.

Measurements made at the middle of the sheath to ground show very little difference in the voltage to ground when F and S are both grounded over the case where S only is grounded. The measured voltages were essentially the same, being 13 and 14 kv.

With a ground at F only, the initial voltage rise was 40 kv. However, the duration of the wave was nearly the same as for the grounding conditions previously discussed.

It may be noted that the duration of the wave when measured at the middle of the cable sheath was much shorter than when measured at S. It may be noted that the measurements made in the middle of the cable were made with a capacity divider.

Plate VIII. Lightning Arresters. In these tests the lightning arresters were composed of a gap in series with a water tube resistance which was connected between the cable conductor and the sheath. Both the gap settings and the resistances were varied during these tests, thus making calculations possible for an arrester having any value of resistance.

Resistance. When a gap with no series resistance was placed between the conductor and sheath, spark-over of the gap started an oscillation in the cable, the fre-

quency of which was determined by the constants of the cable (C-23-18).

With the arrester at F and measurements at S, the reduction in voltage due to the arrester takes place 3 microseconds later than for the case where the arrester was at S. (C-19-2 and 12.)

With the arrester at S, the wave which passed the

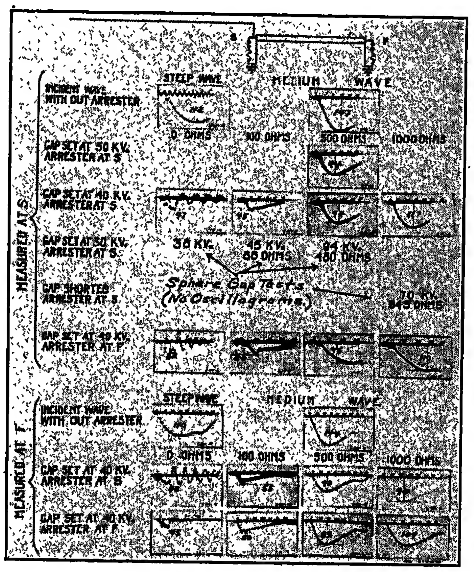


PLATE VIII. LIGHTNING ARRESTERS

arrester was reflected when it reached the open end of the cable, as is shown in C-20-16. The increase in voltage over the gap setting was 15 kv.

Plate IX. Lightning Arresters, Wave Along Line.

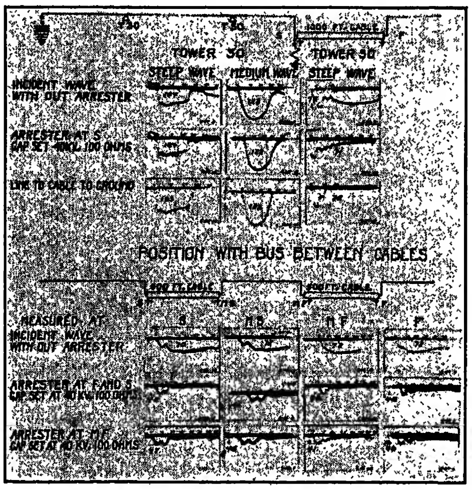


PLATE IX. LIGHTNING ARRESTERS, WAVE ALONG LINE

It will be seen that the reflections with the arrester are intermediate between the conditions with no arrester and with a low resistance ground at the cable end. The degree of similarity with one or the other condition depends on the arrester resistance.

Condition with Bus Between Cables. For this condition the voltage at both ends of the first section of cable was 6 to 7 kv. higher than the arrester gap setting, while the voltage at the start of the second section, at the arrester location, was practically the same as the gap setting. This increase in voltage at points distant from the arrester can be explained for the first section as due to the increase in voltage taking place before the wave of reduction returns from the arrester.

THEORETICAL DISCUSSION

Calculation of the Wave Shape. To calculate the effect that the 1000-ft. length of cable would have on one of the waves and to check the actual oscillograms taken, the following graphical method was used:

The equations for the waves at a transition point are:

Incident wave: e = value at time t.

Reflected wave: $$e' = e\,\frac{1 - \dfrac{Z_1}{Z_2}}{1 + \dfrac{Z_1}{Z_2}}$$

Transmitted wave: $$e'' = e\,\frac{2}{1 + \dfrac{Z_1}{Z_2}}$$

The impedance of the transmission line is taken as

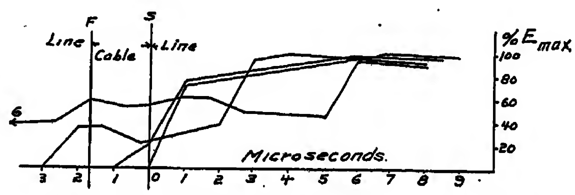


FIG. 5—GRAPHICAL SOLUTION OF TRAVELING WAVE-SHAPE

approximately 620 ohms, and that of the cable as 103 ohms or 1/6 that of the line, which gives:

$e' = -\ 5/7\ e$ for Line to Cable.
$e' = \ 5/7\ e$ for Cable to Line.
$e'' = \ 2/7\ e$ for Line to Cable.
$e'' = 1\ 5/7\ e$ for Cable to Line.

The steep wave as shown by Oscillogram C-27-8 Plate I, is approximately shown by a straight line from zero to 70 per cent in one microsecond, a straight line from 70 per cent to 100 per cent in 6 microseconds, and from 100 per cent to 68 per cent in 23 microseconds. Being measured on a continuous line and neglecting attenuation, this is also the space wave incident to the cable.

The length of time for a point on the wave to travel from one end of the cable to the other is 1⅝ microseconds in space. For the transmission line 1000 ft. is represented by 1 microsecond. In Fig. 5 space waves are shown for various intervals in microseconds after the incident wave has reached the cable, each interval being chosen so that sudden changes at places to be measured will show in the final curves. Each space

wave is made up graphically by drawing the reflected waves with the transmitted wave and adding them together. This becomes a very laborious process after a few reflections have passed back and forth through the cable.

From these space waves curves showing voltage with time can be taken at any point on the line. Fig. 6 shows such curves for positions at the start end of the cable *S*, the finish end of the cable *F*, and for Tower 50. Comparing these curves with the actual oscillograms C-22-14, C-22-8, and C-27-2 as shown on Plate III, the shapes of the waves agree. C-25-15 Plate III, is probably a better picture of what happens at *F*, being only 1500 ft. from *F* and more nearly agrees with the calculated curves. The reduction in voltage shows from 24 per cent to 28 per cent for the oscillograms and 12 per cent for the calculated values. The time for the voltages to reach crest value agrees.

Summary of Results and Conclusions

1. There was no appreciable change in wave-shape with distance for the section of line used. The crest voltage of the waves were close to the critical corona voltage of the line. Hence no great attenuation of crest voltage appears, and very little change in the wave-front. The distance covered by measurement with sphere-gaps and oscillograms was 3.7 miles.

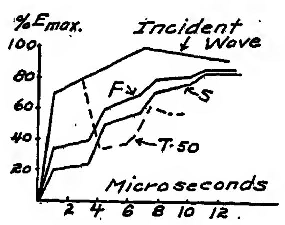


Fig. 6—Graphical Solution of Traveling Wave Shape

2. Attenuation of crest voltage was small. In traveling 3.68 miles the steep wave was reduced 15.5 per cent, and the medium wave was reduced 14.7 per cent.

3. High-frequency oscillations which appear on the front of a steep wave are damped as the wave travels along the line.

4. A wave having a front whose length is short compared to the time required for the voltage to build up in the cable, will be less steep after passing through a cable.

5. The amount of change in wave-front for a wave passing through a cable will depend on:

(a) The steepness of the wave-front.

(b) The length of the crest or near crest of the wave.

(c) The length of the cable.

(d) The values of surge impedance for line and cable.

For a 500-ft. cable the 8-50* wave was changed from an 8-microsecond front to a 12-microsecond front when entering the cable from the line.

For a 1000-ft. cable the 8-50 wave was changed from an 8-microsecond front to a 24-microsecond front when entering the cable from the line.

6. A wave passing through a section of cable will have its crest value reduced unless the wave has a flat top long enough to cover the time required for the cable voltage to build up by reflections to practically the crest value of the incident wave.

For a 500-ft. section of cable the crest voltage was reduced 10.8 per cent for both the steep wave and the medium wave.

For a 1000-ft. cable the crest voltage was reduced 24 per cent for the steep wave, 23.3 per cent for the medium wave, and 17 per cent for the slow wave.

7. The propagation velocity was found to be 600 ft. per microsecond in the cable.

8. When a wave passed into the cable, the initial transmitted wave was approximately 30 per cent of the incident wave. This value is dependent on the surge impedance of both line and cable.

9. The two 500-ft. lengths of cable with a short connection between them had practically the same influence on a wave as the single 1000-ft. length of cable.

10. By inserting a 500-ft. connection between the two sections of cable an oscillation was introduced on the front of the wave passing through the cables. The crest voltages were unchanged by this addition.

11. A short section of cable acts like a concentrated capacity at the open end of a line or at an intermediate point in a line, provided the length of the wave-front is long when compared to the time required for the wave to be reflected through the cable. Such a cable or capacitor does not reduce the surge voltage at the connected point if the incident wave has a long flat top.

12. Short lengths of cable cannot be regarded as protective devices for the reduction of overvoltage surges with long flat tops such as often occur in service.

13. Grounding the sheath of the cable at the start *S* gives the same result as grounding at both ends. When the sheath was grounded at the far end of the cable only, the entering wave, measured to ground, had a higher value. This higher voltage was due to the potential between sheath and ground when the sheath was not connected to ground at the start of the cable. After a few reflections through the cable, the wave assumes the same shape whether the cable is grounded at one end or at both ends. This effect is dependent upon the wave-shape and the length of the cable.

14. A traveling wave in a section of cable may be calculated graphically, if the incident wave is given, and the calculated wave will check the measured waves closely.

15. Arrester operation for any type of arrester may be calculated from the volt-ampere curves obtained under similar conditions.

*Rises to 8 microseconds and decays to half value in 50 microseconds.

16. The increase in voltage at the other end of the cable from the arrester location was about 15 kv. This increase depends upon the steepness of the wave and the length of the cable, and may be estimated for any specific case.

The authors wish to express their appreciation to Messrs. E. J. Wade, W. J. Rudge, F. Osgerby, and J. R. Eaton, of the cooperating companies who conducted the field tests and furnished valuable assistance in preparing the paper.

References

1. E. J. Wade, "Portable Million-Volt Impulse Generator and Method of Initiation," *General Elec. Rev.*, Feb. 1930.

2. K. B. McEachron, J. G. Hemstreet, and W. J. Rudge, *Study of Traveling Waves on Transmission Lines with Artificial Lightning Surges*, A. I. E. E. Trans., Vol. 49, July 1930.

3. R. H. George, *A New Type of Hot Cathode Oscillograph*, A. I. E. E. Quarterly Trans., Vol. 48, July 1929, p. 890.

4. D. Gabor, "Forschungshaft der Studiengesellschaft für Hochstspannungspanlagen," *E. T. Z.*, 1 Heft., Sept. 1927, p. 42.

Discussion

H. Halperin and K. W. Miller: About a year ago the question of surges entering cable from an overhead line arose in connection with the installation of 3300 circuit ft. of 132-kv. single-conductor oil-filled cable. The cable was to be on the end of a forty mile transmission line with 2000 ft. more of overhead line between the cable and the station transformer terminal. Careful theoretical study was given to this problem and the following conclusions were reached:

1. Assuming the cable is perfectly grounded, any incoming surge would be immediately reduced at the cable pothead by an amount corresponding to the standard formulas for surges at a point of change of surge impedance in a line.

2. If the cable, or the entrance end of the cable, were not grounded, the potential of the sheath would rise in such a way that the surge voltage across the cable insulation would be in the ratio of the surge impedance of the cable (conductor to sheath) to the surge impedance of the cable conductor to earth (sheath assumed absent), which is again a great reduction.

3. Intermediate grounding would produce effects intermediate between Items No. 1 and No. 2, but always produce a large immediate reduction of voltage on entrance in accordance with the accepted surge impedance ratio theories.

4. After the surge enters the cable the voltage will build up by reflections in accordance with theory.

5. Except for attenuation effects (which would probably be comparatively small at the reduced voltages with oil-filled cables of high insulation, leakage resistance, and little or no ionization equivalent to corona) the surge voltages produced at all points of the cable would be about equal, and, therefore, there is no useful purpose served in over-insulating the one or two cable lengths adjacent to the potheads.

It is gratifying to read of the carefully conducted experiments of the authors, which substantiate these conclusions based on standard theories.

It is interesting to note the several different values of surge impedance of the test cable which was obtained by the authors from the various methods of measurement. We believe this is due to the fact that the cable sheath cannot be considered as "perfectly" grounded during surges, and, therefore, the actual cable surge impedance lies somewhere between the values obtained from Items No. 1 and No. 2 above, which, in general, are different numerically.

Lastly, it is apparent that the final reduced value of an incoming line surge, including the effects of reflections, will be roughly proportional to the ratio of cable to overhead line surge impedance and inversely proportional to the cable length. For high voltage cables the surge impedance will be about one-half that of the small test cable used by the authors, and the length will ordinarily be from 3000 to 75,000 ft.; so that the final cable voltage will usually be a much smaller fraction of the incoming surge than that found in the authors' tests.

With judicious use of arresters there does not appear to be any excessive danger to the cable in such installations. In some cases, especially for the extra high voltage installations with lengths of underground cable equal to or greater than the length of the surge, arresters appear unnecessary at the junction of the overhead and underground lines. Regarding direct strokes at the junction, which would be very rare, arresters would probably be of little value.

H. G. Brinton: From a theoretical standpoint the effect of a short length of cable is best determined by considering a long rectangular traveling wave. Any other wave shape may be considered as the superposition of a number of rectangular waves.

Considering first the case of an incoming wave E_1 on a line of surge impedance Z_1 passing into a cable Z_2 with no outgoing line connected at the far end. The first wave entering the cable is

$$E_1 \frac{2\,Z_2}{Z_1 + Z_2}$$

This wave is totally reflected at the far end of the cable, doubling the voltage. When the reflected wave reaches the junction with the overhead line, a second wave enters the cable which is

$\dfrac{Z_1 - Z_2}{Z_1 + Z_2}$ times the first entering wave. Similarly there is a third entering wave which is the same factor times the second entering wave, or the factor squared times the first entering wave, etc. Therefore the sum of the series of entering and reflected waves is given by the formula

$$E_2 = 2\,E_1 \frac{2\,Z_2}{Z_1 + Z_2}\left[1 + \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right) + \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 + \text{etc.}\right]$$

Comparing this equation with

$$\frac{1}{1 - b} = 1 + b + b^2 + b^3 + \text{etc.}$$

we see that for a wave E_1 of infinite length

$$E_2 = 2\,E_1 \frac{2\,Z_2}{Z_1 + Z_2}\;\frac{1}{1 - \dfrac{Z_1 - Z_2}{Z_1 + Z_2}} = 2\,E_1$$

If the wave E_1 is long compared with the cable length, the maximum value of E_2 will approach $2\,E_1$ but if the wave E_1 is comparatively short E_2 will be considerably less than E_1 as there will be only a few terms of the above series to be considered. However, in practise it is necessary to consider waves with long flat tops as well as short waves.

Considering next the case of an outgoing line Z_3 at the far end of the cable. The first entering wave is the same as before. The reflected wave starting at Z_3 is equal to the factor $\dfrac{Z_3 - Z_2}{Z_3 + Z_2}$ times the entering wave and the factor giving the sum of the entering and reflected wave is $\left(1 + \dfrac{Z_3 - Z_2}{Z_3 + Z_2}\right)$. Each enter-

ing wave (except the first) is equal to $\left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \; \frac{Z_3 - Z_2}{Z_3 + Z_2}\right)$ times the preceding entering wave. Therefore the formula for E_2 is

$$E_2 = E_1 \frac{2\,Z_2}{Z_1 + Z_2}\left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2}\right)\left[1 + \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \; \frac{Z_3 - Z_2}{Z_3 + Z_2}\right) + \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \cdot \frac{Z_3 - Z_2}{Z_3 + Z_2}\right)^2 + \text{etc.}\right]$$

For an infinitely long wave E_1 the maximum value of E_2 is (at far end of cable at junction with Z_3, $E_3 = E_2$)

$$E_3 = E_2 = \frac{2}{1 + \dfrac{Z_1}{Z_3}}\,E_1.$$

This is equal to $2\,E_1$ when Z_3 is infinity as in the first case considered, and is equal to E_1 when $Z_3 = Z_1$ but is independent of the value of Z_2. Thus we see that for a long flat topped wave the passing of the wave through a short length of cable slopes off the wave front but does not decrease the maximum potential of the wave. This statement also holds for wave of sloping front and long flat top because they can be considered as the superposition of a number of rectangular waves.

L. V. Bewley: The principal difficulty in computing the effect of short lengths of cable inserted in a transmission line circuit, is to keep track of the multiplicity of reflections which occur at the junctions. I have prepared a paper, to be presented at the Pacific Coast Convention, in which a lattice is described which is uniquely adapted to the solution of such problems in multiple reflection of traveling waves. As an example of its use consider the case of Plate IX in the author's paper, where two short lengths of cable (500 ft.) separated by a short length of line (also 500 ft.) are inserted in the circuit. Let

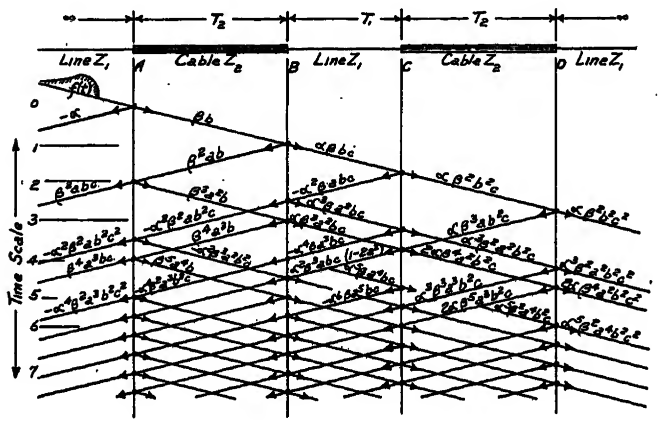
Line		Cable
Z_1	Surge impedance	Z_2
v_1	Velocity of propagation	v_2
L_1	Length of section	L_2
$T_1 = L_1/v_1$	Time of transit	$T_2 = L_2/v_2$
α	Attenuation of section	β
$-a = \dfrac{Z_2 - Z_1}{Z_2 + Z_1}$	Reflection operator	$a = \dfrac{Z_1 - Z_2}{Z_1 + Z_2}$
$b = \dfrac{2\,Z_2}{Z_2 + Z_1}$	Refraction operator	$c = \dfrac{2\,Z_1}{Z_1 + Z_2}$

Now, if the distortion of wave shape due to losses be neglected, then all reflected and transmitted waves have identically the same shape, but differ in magnitude due to attenuation and division at the junction. Referring to the lattice shown in the figure of this discussion, the following facts are evident:

1. All incident, reflected and transmitted waves are traveling "down hill," so that
2. The vertical time scale at the left of the lattice shows the time of arrival of all waves at all junctions.
3. The length of each line or cable section is given in terms of the times T_1 and T_2 that it takes a wave to travel over the section at its velocity of propagation v_1 or v_2. A time axis of length is preferable to a distance axis, because it preserves the slope of the diagonals in the lattice, and thereby avoids considerable interference.
4. Waves on a line section suffer an attenuation (α).
5. Waves on a cable section suffer an attenuation (β).
6. Waves reflect from a line-cable junction by a fraction ($-a$).
7. Waves reflect from a cable-line junction by a fraction (a).
8. Waves transmit across a line-cable junction by a fraction (b).
9. Waves transmit across a cable-line junction by a fraction (c).
10. The lattice "converges" to a constant density of diagonals.
11. The total voltage at any junction at any time is obtained by superimposing all waves on one side of that junction, displaced from each other by the time lag representing their instants of arrival at the junction.

Equations for the total voltage at each junction, as function of time, are given on the lattice. In these equations $f(t)$ is the shape of the initial incident wave arriving at junction A, and $f(t - T)$ represents exactly this same wave arriving at any junction an instant T later. However, each of these functions are multiplied by some fraction involving the reflection and refraction operators a, b, c.

As an example of how the waves are added, the first three waves arriving at junction A are shown superimposed at their proper time intervals at the bottom of the figure.

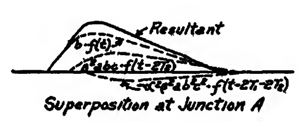


$$e_A = b\cdot f(t) + \beta^2abc\cdot f(t-2T_2) - \alpha^2\beta^2ab^2c^2\cdot f(t-2T_1-2T_2) + \beta^4a^3bc\cdot f(t-4T_2) - \alpha^4\beta^2a^3b^2c^2\cdot f(t-4T_1-2T_2) + \cdots$$

$$e_B = \beta bc\cdot f(t-T_2) - \alpha^2\beta ab^2c\cdot f(t-2T_1-T_2) + \beta^3a^2bc\cdot f(t-3T_2) - \alpha^4\beta a^3b^2c\cdot f(t-4T_1-T_2) + \alpha^2\beta^3ab^2c(b-3a^2)\cdot f(t-2T_1-3T_2) + \beta^5a^4bc\cdot f(t-5T_2) + \cdots$$

$$e_C = \alpha\beta b^2c\cdot f(t-T_1-T_2) + \alpha^3\beta a^2b^2c\cdot f(t-3T_1-T_2) + \alpha\beta^3ab^2c(a+c)\cdot f(t-T_1-3T_2) + \alpha^5\beta a^4b^2c\cdot f(t-5T_1-T_2) + \alpha^3\beta^3a^2b^2c(3a^2-b)\cdot f(t-3T_1-3T_2) + \cdots$$

$$e_D = \alpha\beta^2b^2c^2\cdot f(t-T_1-2T_2) + \alpha^3\beta^2a^2b^2c^2\cdot f(t-3T_1-2T_2) + 2\alpha\beta^4a^2b^2c^2\cdot f(t-T_1-4T_2) + \alpha^5\beta^2a^4b^2c^2\cdot f(t-5T_1-2T_2) + \cdots$$



$a = \dfrac{Z_1 - Z_2}{Z_1 + Z_2}$

$b = \dfrac{2Z_2}{Z_1 + Z_2} = 1 - a$

$c = \dfrac{2Z_1}{Z_1 + Z_2} = 1 + a$

α = attenuation of line section

β = attenuation of cable section

FIG. 1

It is obvious that it soon becomes impracticable to show all the coefficients directly on the lattice itself, but this disadvantage can be circumvented by numbering the arms of the lattice, and computing the actual coefficients in a table. In fact, it is usually possible to devise tabular methods (with the lattice as a basis) in which the procedure is automatic.

The scheme does not take into account the distortion which the waves experience as they travel along the circuit.

The lattice may be applied to complex junctions, including combinations of inductance and capacitance, but in such cases the reflection and refraction coefficients become operational expressions involving the time derivative ($d/d\,t$).

C. Francis Harding: Three distinct and most valuable contributions to the understanding of extra high voltage phenomena have been presented in this paper:

1. The cathode-ray oscillograph, particularly that operating

upon the hot-cathode principle developed by Mr. R. H. George of Purdue University has been thoroughly tried out and found to be not only dependable but practically irreplaceable as an instrument for either laboratory or field investigations of extra high voltage surges which have a duration of from one to 100 microseconds. Previous investigations making use of this same type of oscillograph considered in conjunction with the disclosures of this paper demonstrate its practicability for reproducing with accurate calibration the magnitude of such potentials and the time of duration of steep-wave-front surges whether of natural lightning or of those initiated by means of a lightning surge generator.

2. The theoretical calculations of the attenuation and reflection of steep-wave impulses, which in the past have been made with some doubt regarding the accuracy of the assumptions necessary for a concrete solution, have now been definitely confirmed by practical test values. The calculations of the past therefore take on more authenticity, and those of the future, although rendered less necessary than before, will be undertaken with more confidence.

3. The practicability of predetermining the constants of inductive reactance and equivalent resistance necessary to produce surges of desired wave-fronts and duration, duplicating typical lightning exposures, and the readiness with which such impulses are repeated time and time again with the surge generator for comparative testing purposes in the field are now well established.

With these possibilities demonstrated, it should not be long before surge tests of transmission lines and cables, insulation, lightning arresters, etc., may be more accurately standardized and their laboratory tests more readily duplicated.

Unfortunately, we are still dependent upon the rather unsatisfactory standard making use of the sphere-gap for high voltage measurement. Particularly with small spheres and steep-wave-fronts of relatively low voltages, such as from one to fifty kilovolts, such instruments are too variable for use as standards. This is especially true for use in the field where preionization of the gap is not always practicable.

The writer has found in the high-voltage laboratory of Purdue University, for example, that in the sphere-gap measurement of such ranges of potential of steep waves, impressed upon a circuit by the lightning generator, several experienced investigators may introduce a personal error of from fifteen to twenty-five per cent if the gap is not preionized and artificially ventilated, whereas the addition of such precautions would reduce the error of six such observers to within two per cent.

Although the relative values set forth in this paper did not require a high degree of accuracy, the statement that small sphere-gaps were used for some measurements raised a question which should be given careful consideration in subsequent laboratory testing, particularly in the standardization of extra high voltage measurements and their application to lightning arresters, insulators, etc., which are to be subjected to surge potential exposures.

K. B. McEachron: It is interesting to note the agreement which Messrs. Halperin and Miller find between their calculations and the field tests. Their conclusion that the final value of the incoming surge will be roughly proportional to the ratio of cable to overhead line surge impedance and inversely proportional to the cable length is true for a given length of incoming surge. It is, however, apparent that the ratio of surge length to cable length is important; the greater this ratio the higher the cable voltage will be. Thus with very long transients the cable potential may finally equal the incoming surge potential.

The lattice which Mr. Bewley describes is useful when calculating the effect of reflections at transition points, and should help to simplify the rather laborious process of calculating reflections of traveling waves.

Professor Harding is rather more pessimistic about the accuracy of sphere gap measurements than our experience indicates. A rather wide experience with gaps has demonstrated to us that cleaning the electrodes frequently will give reasonably constant results with better consistency than indicated by Professor Harding.

H. P. Seelye: The method indicated in this paper of making a graphical analysis of the passage of a lightning surge through a short section of cable is of practical value in studying many other cases of a similar nature. For example, it has been used in investigating the effect of short lengths of ground wire and of both ground wire and cable at the station end of a line.

The application of this method, although involving some complications in the multiplicity of reflections involved, as pointed out by Mr. Bewley, is relatively simple in theory and not unduly difficult to carry out.

It has the advantage over the use of a rectangular wave in that the wave with sloping front and finite tail more nearly simulates the actual lightning wave. The slope of the front, height of crest and length may be chosen to best fit the conditions of the problem, *i. e.*, to show the worst condition, the average condition, a wave chopped by lightning arresters, or any other variation. Since the field test proved the accuracy of the underlying assumptions and theory, the results of such a study may be depended upon as a true picture of the actual action of the wave chosen.

Dancing Conductors

BY A. E. DAVISON*
Associate, A. I. E. E.

Synopsis.—The phenomenon of dancing cables is discussed; the merits of different theories are considered, reference being made to the theory that vibrations of small amplitude, but relatively high frequency, travel along the line to points where the constants of the line change as at dead-ending insulators and there reflect and combine into slower waves of great amplitude. The suggestion is made that much experimental work should be done with regard to these theories before drawing any definite conclusions.

Reference is made to Magnus effect and to the "lift" of ice-coated cables in wind storms. This lift, perpendicular to the direction of the wind, is carefully considered, and diagrams show experimental values of this lift on models similar to the ice-coated cables. The diagrams indicate variations and reversals of this thrust due to small changes of angle of the specimen to the direction of the wind. The suggestion is made that these alternate lifting and depressing effects should be considered as the cause of some, if not a large percentage, of the phenomenal movements of ice-coated conductors in relatively light winds.

As in most earlier reports and discussions there does not seem to be any remedy as a result of this study, other than that of heating the conductor electrically throughout sleet-forming periods to such a temperature that the sleet cannot form on the wires.

Introduction

Dancing or galloping conductors have been recognized and studied for a number of years. The problem is mechanical, but it is of great interest to electrical engineers. The phenomenon commands attention because of the serious outages and resulting damages and losses which it is liable to cause. With the exception of earthquakes and holocausts, it is, in the opinion of some, the most serious although not the most frequent cause of outages on important transmission lines. When the phenomenon occurs, the cable span oscillates sometimes as a whole, but more frequently with one or more nodes in a span. It is frequently described as whipping, jumping, floating, dancing, or galloping. When the oscillations become severe, the cables will move irregularly, but freely, through vertical distances of as much as 20 to 25 ft. in spans of 500 ft. An elliptical motion with longer axis of the ellipse vertical is usually observed as the motion of a point on the cable with the result that at any moment two wires of a circuit may come in contact, especially if there is vertical configuration of the conductors. Furthermore, even if the conductors do not come in contact electrically, the movement is sometimes sufficient to tear the cables from the fastenings. Mechanical failures may not always occur; however, if the weather conditions continue for any length of time, the movements are liable to cause such deterioration and loosening of the structures and fastenings that it is necessary to overhaul the whole section of the line affected.

The phenomenon cannot be observed every day, nor can it be seen at any specific place; it appears and disappears suddenly and we have good reason to believe that weather conditions may account for most of the trouble. The difficulty of being "on the spot" when galloping occurs may account for the small amount of accurate data and observations on which we have to work. Few indeed who have studied the phenomenon have ever seen it more than once. It is therefore necessary that the transmission engineer arrange laboratory equipment by which the condition may be reproduced at will, after which he can set himself the task of devising a remedy.

Review of Theoretical Considerations and Published Data

Attempts have frequently been made to connect this galloping with the minor vibrations which are always or nearly always present in catenaries, especially during very light winds (four miles per hour) and presumably during rising temperatures. It is argued by some that these accumulate in the vicinity of dead-ends, or other changes in the characteristics of the line. By reflection, or other condition, amplitude and wavelength are multiplied many times and finally with many irregular movements they break up by doing work upon the fastenings.

Varney[1] has familiarized engineers with these small vibrations (a sort of resonance condition) while making studies to reduce the effects which these smaller vibrations have upon the conductors at clamps and other points where the mechanical constants change.

Knowlton[2] discusses the application of Magnus theory as accounting for these smaller vibrations much as it is used herein to account for the irregular movements of greater magnitudes.

Semenza is credited with having first advanced a quite different theory that these smaller motions (sometimes called the natural or fundamental vibration of a line) are caused by longitudinal mechanical pulsations put into the line by changes in the mechanical tensions due to the swinging of the cables in light winds.

A span may be swinging at some relatively slow angular velocity during each cycle of which there are changes of tension in that particular span. The local tension is a maximum near the lowest point of the swing and least, reaching almost zero, when the motion

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

1. For references see Bibliography.

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reverses, especially if the arc of the swing should become greater than 180 deg. These alternate increments and decrements of tension send out into adjoining spans pulses of varying frequencies depending upon such physical conditions as length of spans, wind velocities, and temperatures.

When several groups of these mechanical pulses are transmitted the increments and decrements of tension are in some cases counteracted and in other cases they combine to give rise to a resultant well-defined wave of tension. The question of how much damping occurs during this process of combination and eliminations to give the resultant natural frequency wave has not been studied but if, as some appear to believe, this tension wave can travel along the line without much loss of energy, then it may travel great distances. Semenza may not have carried the idea further. However, if the frequency of this wave be the natural frequency of one of the spans through which it passes, then it is conceivable that this span will respond to this high frequency and start oscillating as a whole or with only one or two nodes at much lower frequency.

Darling[3] accounts for a particular case which was on a wood pole line, by assuming that the swaying of the poles in the wind caused the trouble and that the remedy was therefore to brace the poles in the direction of the line.

Hawley[4] discusses an interesting case which he saw near a railroad. He thinks that the direction of the wind in relation to the direction of the line is important, as only those spans running diagonally with the wind were dancing. The motion was mainly vertical. He suggests that in practically all cases two or more adjacent spans were jumping. The exceptional feature was that the temperature was well above freezing and there was a "pulsating" wind blowing. He is definitely of the opinion that the energy was supplied by horizontal air movements upon conductors having uniform surface throughout the circumference. He seems of the opinion that the pulse of wind striking first one span and then the next was the cause of the motion.

Sothman[5] goes so far as to assume a critical temperature in the cable and considers the ice to function as insulating covering. He later lays great emphasis on a critical tension as being the cause of dancing and also does not regard an ice-coating as essential. Electrical causes such as surges are also discussed in his letter. Surges undoubtedly do cause abnormal movements. He calls attention analogously to the uplift in underground cables due to electrical causes throwing cables six inches out of the ground after some months of operation.

Another suggested cause of dancing is the vibration caused by railway trains or other like jarring movements, such as power generating plants or manufacturing plants connected with the wires. Causes of this type are discussed by Ferrier and Haussadis[6] and by Archbold.[7] Extraordinary movements may be started by gusts of wind actually lifting parts of a span or by large pieces of melting ice falling from a cable. Movements of this sort, as well as those resulting from electrical surges, are not usually sustained and repeated many times. Such conditions may be familiar to observers and are consistent with the effects which might be expected from abnormal atmospheric or other disturbances. These conditions are, however, well out of mind when the observer is watching "galloping" conductors. Quite another set of conditions is evident and happenings are phenomenal.

Many of the suggestions and theoretical considerations reviewed above regarding causes and effects have merit and it is not intended that efforts should be abandoned to connect up the small rapid vibrations with boisterous galloping, which is almost sure to cause short circuits and grounds and even do mechanical damage to structures. Standing waves and almost every sort of odd and exaggerated performance may be observed in 100 ft. or so of a light rope or line, supported at intervals by vertical strings comparable to suspension insulators, when very small mechanical impulses are put into the line at one end, the other end being fixed. These vibrations can be introduced quite effectually as the result of either longitudinal or transverse impulses. The latter especially require very little effort. As a result of this review of data, it becomes evident that no theory has yet been found by which the accumulation of small vibrations into galloping can be substantiated by calculations and experiment. This may, however, be done later by the use of satisfying assumptions, and through further experiments and supporting calculations. Further work along this line will doubtless be quite profitable and it is not intended that any suggestion or result recorded in this paper should in any way check further study and development of these ideas.

Comparative Study of Phenomenal Movements

In the meantime, two instances of extraordinary movements of conductors were reported by E. G. Archer of the Hydro-Electric Power Commission during the latter part of 1927, one at Whitby and one at Niagara Falls. The case at Whitby showed violent swinging. The temperature was well above 60 deg. fahr. and there was a gale. Conditions were evidently quite similar to those which Haussadis had in mind.

At Niagara Falls, with a wind of approximately 30 mi. per hour blowing nearly at right angles to the line and accompanied by a fine sleet, a condition was observed which was so peculiar that it commanded attention. Two tower lines supported one circuit each and a third tower line carried two circuits. All cables were supported by suspension insulators and the tower lines paralleled one another closely. One circuit on a single-tower line and one of the circuits on the double-circuit line were dancing. The other circuit on the double-circuit line had been reported as dancing earlier in the day but had stopped. The dancing was localized

to one span and the motions did not appear to be transmitted to the adjacent spans. The suspension insulators were not moved out of line although the dancing appeared to carry the cables vertically at center of four to five hundred foot spans approximately 15 ft.

These two observations separated by only a few months were so different as to weather conditions and resulting phenomena that the observer suggested that some explanation should be sought for the extraordinary

FIG. 1—WHIPPING OF CONDUCTORS AT HAMILTON

whipping during relatively light winds at Niagara Falls.

He suggested that so long as the cables were smoothly glazed on one side and left rough, as in stranding, on the other side, there would be galloping due to Magnus effect. If later the cables, due to moving around freely under these conditions, became coated all over then that particular span would show much less movement.

RECORDS OF GALLOPING

H. J. Muehleman of the Hydro-Electric Power Commission was fortunate in securing a photographic record of extraordinary movements of conductors—605,000-cir. mil A. C. S. R., 110-kv. crossing at Hamilton, Ontario, Fig. 1. This photograph was taken at the same time that Archer was observing galloping at Niagara Falls, some 40 mi. east. Muehleman reports a thin coating of ice on parts of the conductors. As is usually observed when conductors are moving violently, one or more wires are quiet in each span. In some cases the conductor on each side of the dead-end is vibrating while in other cases it is vibrating on one side of the tower and not on the other.

The span on the right is 200 ft. long, that on the left approximately 500 ft. Both spans were dead-ended at each end and there was a change of tension as well as a change of direction in the line of 10 deg. at the towers which appear in the photograph.

LIFT OF PARTIALLY COATED CONDUCTORS INVESTIGATED

Archer urged the taking of measurements, to confirm these assumptions, in a wind tunnel which was available at the University of Toronto. A specimen was prepared. It consisted of a piece of conductor left rough over one half of its circumference. The other side was made smooth and varnished, approximating the partial coating of glaze which was noticed on the conductors. Experiments of this sort had already been suggested by Knowlton.[2] This was done and the results are indicated in Fig. 2. It is clear from the diagram that for certain quite small angles of rotation of the coated conductor in a steady wind the variations in lift and in depressing effects are relatively large and rapid.

In Fig. 2, it can be seen that on either side of zero degrees, there are changes in lift from minus 0.085 to plus 0.088, and from minus 0.13 to plus 0.07, being 15 to 20 per cent of the weight of the cable. Catenaries, especially when supported by suspension insulators which readily swing away from and into the span, are not very stable when subjected to rapidly reversing vertical forces even if these forces are relatively small, as compared with the weight of the cable and as in the case of the cotton line may be expected to dance or gallop as a result of application of the relatively small but rapidly reversing forces. There was as a result of this investigation considerable evidence that the partial coat of glaze might be a sufficient explanation of the extraordinary conditions observed at Niagara Falls.

RELATION BETWEEN GLAZE STORMS AND GALLOPING AND CLASSIFICATION OF DATA

A study of reports by over thirty observers, including those reported by Archbold which is by far the largest group, establishes the fact that in 78 to 80 per cent of the cases reported sleet existed on the wires, was being

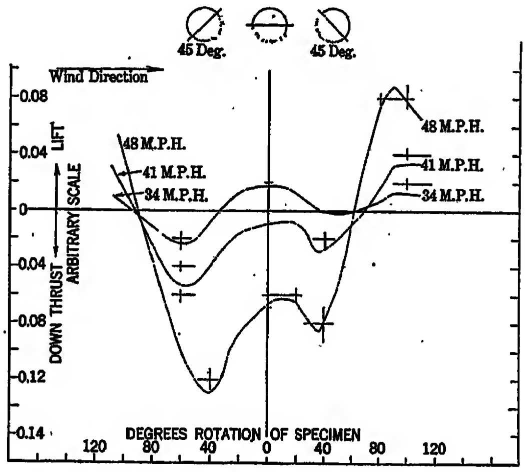

FIG. 2—"LIFT" CURVES FOR CONDUCTORS THINLY GLAZED ONE SIDE ONLY

Half surface smoothed with plasticene to represent ice

deposited in the district, or might be expected because the temperature was 32 deg. and the weather misty and damp.

Archer's observations cover two classes of whipping, the first being in warm weather with violent winds and with flyings moving about freely. He expected that the wires would be shorted or grounded, because of comparatively restricted clearance. They, however, did not go out of service.

In the other case there was no reasonable explanation immediately available, so far as weather was concerned,

why the conductors should be so "possessed" or why some wires in a span were quiet, and others moved vertically as much as, or more than, the total sag at rest. Fine mist or rain was falling and there was a wind storm but no such wind storm as had been recently observed at Whitby. There was, however, no likelihood of the circuits remaining in service at Niagara as long as the weather conditions continued as they were.

It is therefore proposed that in general, reports of abnormal movements in conductors shall for purposes of analysis be classified and as far as can reasonably be done, grouped with one or other of these two observations of which the latter typifies the larger group. If ice is to remain on the conductors for any length of time, then the group represented by the observations at Niagara Falls is by a considerable amount the most important as far as outages are concerned.

Varying Shapes and Cross-Sections of Ice-Coating on Conductors

During several days centering around December 19, 1929, a rather extended and troublesome sleet storm occurred in New York and Ontario districts, centering as far as effects upon transmission lines were concerned in the Niagara River area. There were in this area many opportunities, extending in some cases over more than one day, to study galloping conductors and the effects of these extraordinary movements on conductors and structures. The writer was fortunate to be at Allanburg, which is near the mid-point of the Welland Canal, Fig. 3, on the morning of the twentieth. Repair men were, with great difficulty because of ice on towers, cold weather, snow, and wind, restoring a

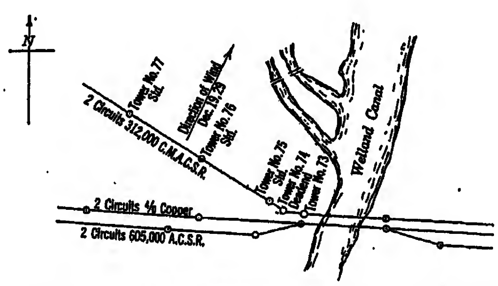

Fig. 3—Location of 110,000-Volt Lines at Welland Canal Crossing

312,000-cir. mil A. C. S. R. conductor which had been burned off near the end of the middle third of a 630-ft. span. This circuit some 40 mi. in length had given practically uninterrupted service for 18 years, excepting occasional momentary outages due to lightning. Two wires of a 110-kv. circuit were in a nearly vertical plane with 8 ft. separation, being part of a triangular configuration.

The conductor which had parted, along with many other conductors and static wires, forming parts of seven quite closely associated high-voltage circuits, were all coated with smooth ice of quite variable cross-section, which had apparently been considerably worn down by wind and weather, having been deposited one or two days previously. In some typical cross-sections which were about 2 in. long, there were two fairly sharp points at each end of the ice envelope. One of these evidently was a drip or series of icicles, and was a maximum radial distance of 3/4 in. from the surface of the conductor. The other abrupt angle was opposite the drip and was not nearly so marked. It was generally not more than 3/8 in. radial distance from the surface of the conductor. Usually there was a thin coating of glaze on all sides of the conductor. A typical cross-

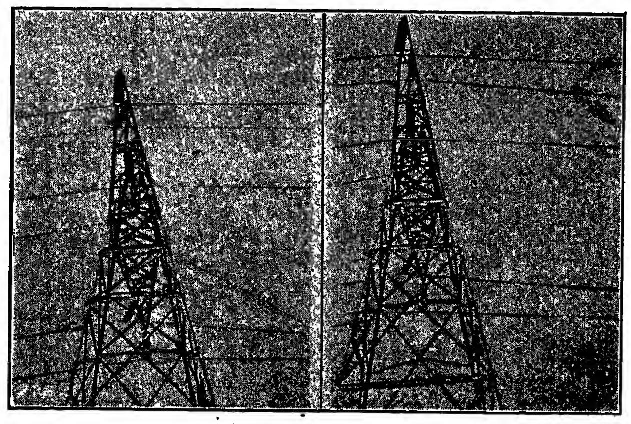

Fig. 4—Insulator Swinging Along Line—Middle Phase Near Side of Tower—Companion Illustration

section might, to some, look like a small bird crouching or clinging close to the conductor.

The 312,000-cir. mil A. C. S. R. conductors which remained intact in this span were moving about very freely in a comparatively light wind, 30 mi. per hour, at 75 deg. to line, to such an extent that repair men were scarcely in a position to report the circuits as available for operation or test under load after repairs had been completed. The phases with vertical configuration were not always clear of one another so long as weather conditions continued as they were. With a loaded sag, equivalent to a uniform ice-coating of about 7/16 in. radial thickness, of 18 to 20 ft. the conductors were moving through vertical distances reported after study by several as from 20 to 25 ft. There was a slow elliptical motion, with a small horizontal axis of the ellipse. The period was irregular but generally three seconds for a cycle. The suspension insulators were moving away from and into the span as much as 30 in. total swing at the point of support of the conductors, as may be observed in the companion photographs, Fig. 4, by referring to the middle phase near side of tower. The cycle of insulator swing was about three seconds. In most cases the whole span was moving upwards and downwards with irregular speeds, especially in the upper portions of the cycle. In other nearby spans, the conditions were much the same with some evidence of a sort of galloping, that is, one-third of a span would lift and as it reached its highest point and commenced to fall the central part of the span

would be moving up towards its high point and so on, giving the effect of a traveling wave. This continued until in the course of several hours the wind changed.

During all this time, the 5/16 in. static wires on each of three nearly parallel lines of towers, including this one, the pair of 4/0 copper conductor circuits and six 605,000-cir. mil A. C. S. R. conductors of the third pair of towers, were all quiet. That is, they were swinging out of plumb about 20 deg. and moving about only a little in that position on account of a somewhat variable wind.

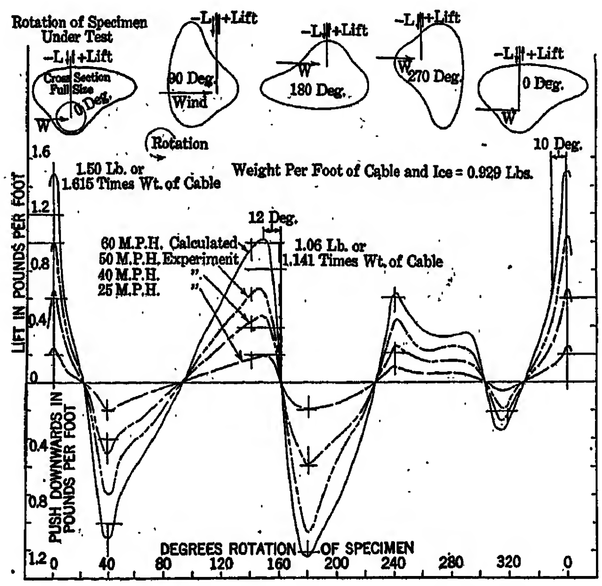

Fig. 5—"Lift" Curves for Special Shape of Ice-Coating on Conductors

Data from tests on model of ice covered transmission wire by Dept. of Mechanical Engineering, University of Toronto (Gravity balanced out)

Effect of Wind upon Cable and Ice Having Irregular Outline of Cross-Section

It was evidently necessary, as the result of these observations, to study some of these irregular shapes and cross-sections in the wind tunnel. The succeeding cross-sections along the conductor were very irregular, resulting in a somewhat saw-toothed effect on account of the drip and icicles. A typical shape was chosen and a specimen 18 in. long was made of full size cross-section. Gravity was balanced out as is customary in examining airplane models and the curves shown in Fig. 5 were secured for 25, 40, and 50 mi. per hour, these having been corrected to per foot basis so as to compare with recorded cable data. A curve for 60 mi. per hour was calculated and added.

With this type of cross-section, the resulting lifts and the pressing down were very much greater than Fig. 1. Selecting for study the extreme case of 60 mi. per hour, there are for changes in rotation of 10 deg., a total change in lift of from plus 0.65 lb. per foot to plus 1.50 lb. per foot, or a total change of 0.85 lb. or 0.91 times the weight of the cable and ice combined. Taking another part of the curve there is for changes in rotation of 45 deg., a total change in lift from minus 0.38 lb. to plus 1.50 lb. This is 2.02 times the weight of the cable and ice combined. Examining lift only, it is evident that there would be at 60 mi. per hour and at considerably lower velocities, sufficient lift to carry the cable with its load upwards indefinitely so long as the angle of presentation to the wind can be maintained within close limits.

Variations in angles of effective presentation of ice surface to wind of 10 deg. and 45 deg. are mentioned. The more effective lifts are, however, confined to much smaller changes of angles of presentation just as in airplane work there is little margin in maintaining equilibrium at critical flying speeds. It would therefore appear that the neighboring copper conductors, the larger aluminum conductors, and the three ground wires, including that one serving the conductors in question, did not naturally present that critical angle, limited say to 6 deg. in 360 (one in 60 chances) for effective lift. They remained relatively quiet, although they did carry somewhat similar ice-coatings. The cables causing trouble were apparently poised so that the lift was effective when the forces due to horizontal wind pressure and gravity were stabilized. As the cable rises due to the lift becoming effective, the angle of presentation is actually changed a few degrees because of rotation of pendulum of the catenary around the point of support of insulator at the tower. The tension in the conductor may have been so changed that there is also a slight rotation because of uncoiling of lay of the cable; this latter feature, however, has not been investigated. The result of this slight change of angle is that the cable is relieved of the upward force and falls by gravity. It may even be thrust down by the wind, the rotation and

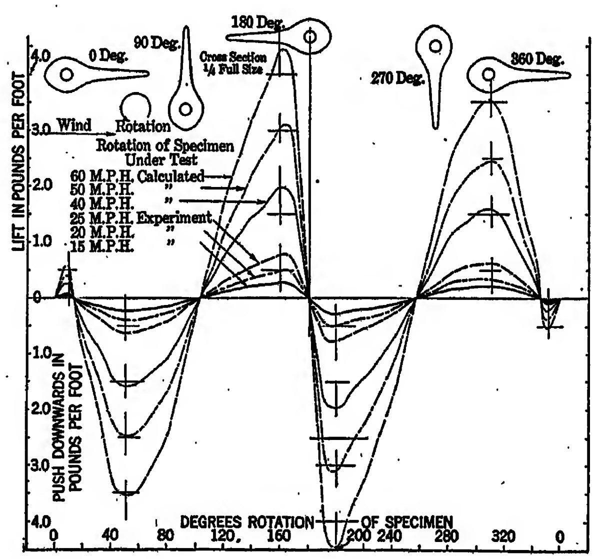

Fig. 6—"Lift" for Heavy Symmetrical Coating of Ice on Conductors

Data from tests on model of ice covered transmission wire

resulting change in presentation having gone through the neutral point of the lift curve.

A shape of ice-coated conductor which gave much trouble during the storm of 1922 was taken from the records of that storm and a specimen for test was made. This cross-section was much more regular and was symmetrical. These tests, Fig. 6, show characteristics somewhat similar to those found in Fig. 1.

Natural forces duplicating the lifting effect observed in galloping conductors have been demonstrated in the wind-tunnel and have been calibrated and recorded. The phenomena may be intelligently reproduced at will and may be studied and measured. Once problematical conditions can be duplicated experimentally in the laboratory and measured they are in a fair way toward being understood and solved. These curves are submitted for further study with a view to ultimately disposing of a quite serious menace to continuity of service of important overhead trunk transmission lines.

Remedies

As in Archbold's letter to the technical press, so here there does not appear to be any ready remedy for the conditions reviewed in the latter part of this paper other than to arrange that during sleet periods, where wind is involved, important circuits shall be kept by artificial electrical loads, or otherwise, at temperatures at which sleet cannot form on them. Operating companies have had considerable experience melting sleet off wires after it has formed, but this is dangerous if there is any vertical configuration, because the sleet load in falling may so relieve a conductor that it will jump up sufficiently close to another conductor which is still carrying a sleet load to cause a short circuit even if there be no wind.

It is possible to keep conductors at temperatures by which sleet will not form. The year 1922 was rather disastrous in the Niagara district as far as transmission lines were concerned. Practically every tree in many square miles was more or less seriously damaged by sleet. Early in that storm overloads reaching 100,000 kv-a., 1900 amperes per sq. in., were placed on this 312,000-cir. mil A. C. S. R. circuit which experienced an outage in 1929. It gave uninterrupted service at that time through two quite long sleet storms during which there was much trouble in other circuits, especially in a paralleling pair of 4/0 copper circuits which were new and had not up to that time been placed in service. Reports from various sources indicate that sleet will melt off slowly and fall when copper is carrying 4000 to 6000 amperes per sq. in. Apparently ice having formed can be melted sufficiently to fall from aluminum conductors after they have carried from 2000 to 2500 amperes for a time even when the air temperatures are 10 or more degrees below freezing. This latter statement compares favorably with the figure of 1900 amperes per sq. in. which was an actual operating condition for many hours. From 4000 to 6000 amperes per sq. in. is not good practise for any purpose as joints may be overloaded.

Conclusion

The stated purpose of this paper was to record the steps necessary to reproduce the conditions observed in the field and provide a yard-stick by which studies can be made to develop effective means of insuring service during sleet storms. This purpose has to some extent at least been accomplished. Some procedure should be developed by further studies which will be less hazardous, difficult, and inconvenient than that of overloading the circuits.

Acknowledgment

The suggestions made by Mr. E. G. Archer account very largely for the work done in preparing the data for this paper. His assistance in assembling the data for the article is also gratefully acknowledged.

Bibliography

1. A. I. E. E. Jl., May 1928.
2. A. I. E. E. Jl., October, 1926.
3. *Electrical Wld.*, April 13, 1929, p. 744.
4. *Electrical Wld.*, March 23, 1929, p. 599.
5. *Electrical Wld.*, June 29, 1929, p. 1341.
6. High-Tension Congress Report, Paris, 1927.
7. *Electrical Wld.*, Jan. 26, 1929, p. 199.

Rationalization of Station Insulating Structures

With Respect to Insulation of the Transmission Line

BY C. L. FORTESCUE[1]

Fellow, A. I. E. E.

Synopsis.—The purpose of this paper is to present a logical basis for the insulation of transmission lines and substations using as a basis the characteristics of traveling waves produced by lightning discharges. The method presented was formulated from the data obtained from the cathode ray oscillograms of actual line surges and upon the laboratory work in which the impulse flashover characteristics of insulating structures was determined. The breakdown volt—time characteristics of various forms of insulation are presented. Using these curves of various forms of gaps in the known characteristics of traveling waves, insulation of the transmission line at various distances from the gap is determined so that flashover will be unlikely to occur at these points. A similar method of analysis is made upon substations and lines protected by lightning arresters, but with the known characteristics of lightning arresters, the insulation on the line up to points 1000 to 5000 ft. away can be apportioned so that the lightning arrester will take the discharge, preventing the flashover of insulation. The system set forth in the paper enables the transmission engineer to design the line and substation in an economical manner and obtain adequate protection for all points desired.

Introduction

The increased amount of information on lightning phenomena which has been obtained during the last few years has given engineers a new insight into the problems of insulating transmission lines and station insulating structures against lightning. It is now becoming common practise to vary the insulation of the transmission line itself to correspond with the severity of the exposures which occur at different points along their lengths. The improvement in the insulation of transmission lines has created some concern in the minds of manufacturers of transformers as to the severity of the surges which as a result of the increased insulation will have to be met by the insulation of station apparatus, and it would be wise to limit the insulation of the transmission line to correspond with the voltage class of the apparatus installed in conformity with the results of past experience with apparatus in the field. The suggestion has been made to limit the insulation of the transmission line for a half a mile outside the station.

Comments on Proposed Procedure

There has been some criticism of this procedure on the part of some engineers on the score that where lightning arresters are used to protect the station apparatus it is unnecessary to cut down the insulation of the transmission line in the neighborhood of the station. However, this argument is not very logical for the reason that as regards insulation the presence of the lightning arrester in itself cuts down the requirements of the substation and nearby points on the transmission line for the reason that the protection afforded by the lightning arrester extends to some distance from its point of instalment. The particular phase of this subject dealing with the protection afforded by lightning arresters at points some distance away will be discussed later on in this paper.

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

The Use of Lightning Arresters Mandatory

At this time the author wishes to point out that as a protective measure for the transformers, the reduced insulation is not intended to replace the lightning arrester, but is intended as a back-up protection and in case something happens to the lightning arrester. It should not be assumed that an insulator string constitutes a good lightning arrester, as its flashover time lag characteristics are not conducive to its functioning as a lightning arrester. This will be easily seen by reference to Fig. 1 in which the flashover of a string of insulators and the surge potential of the corresponding

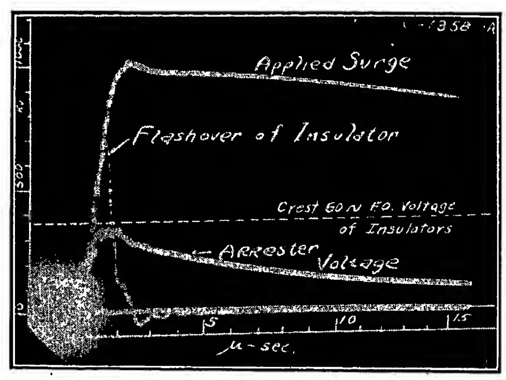

Fig. 1

lightning arrester are shown, as well as the full wave to which they were subjected. A further consideration of the characteristic curves of insulating structures will make this still clearer.

Wave Shape of Lightning Surges as Shown by Lightning Investigations

The lightning investigations carried out in 1928 and 1929 show that contrary to previous ideas, the lightning wave is not of short duration, but may last for 50 microseconds. In particular the wave obtained in 1928 at the Tennessee lightning investigation station had a duration of 50 or 60 microseconds and its value was reduced from its crest by less than 20 per cent. The

waves obtained in our lightning investigation station at Stillwater and other waves obtained in Tennessee have confirmed the general shape of this particular lightning wave. With few exceptions, the more severe waves are of considerable length. To illustrate, some of the waves obtained at Stillwater and Tennessee are reproduced here from the paper by Cox and Beck[2] as Fig. 2.

Laboratory Work to Determine Impulse Flashover Characteristics of Insulating Structures

Our laboratory work on lightning has been carried out on the proposition that the characteristics of insu-

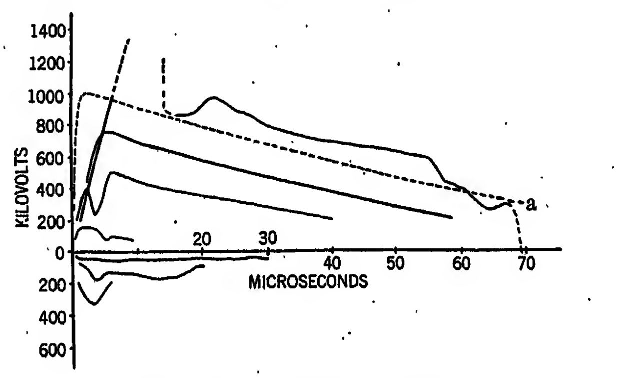

Fig. 2—Lightning Waves

"A"—Trafford Laboratory Wave

lating strings should be based on the most severe type of lightning that is likely to be encountered. This has a further advantage, in that the curves obtained in this manner are drawn in volts and time lag of flashover, and completely specify the impulse time lag characteris-

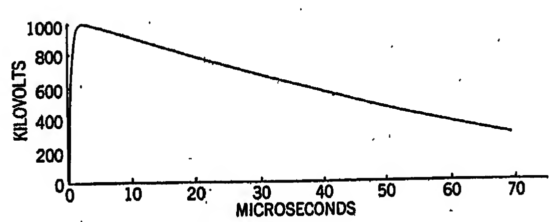

Fig. 3

tics of the insulating structure or insulator without regard to the shape of the wave, and the behavior of the insulator string for any shape of wave can be very easily obtained from these characteristics.

The laboratory work on impulse characteristics was done with the wave shown in Fig. 3. It will be seen that this wave corresponds very closely to a square-topped wave, and is not very different from the wave shape of the lightning surge obtained in Tennessee in 1928, except that the front of the latter may have been longer than indicated. The procedure for obtaining flashover voltage time-lag characteristics is completely described in a contemporary paper by J. J. Torok.[3] It is obviously of great importance for transmission engineers to know the flashover voltage time-lag characteristics of the various types of insulating structures that enter into their transmission line and station designs. During the past two years, a great many data of this type covering the flashover voltage time-lag characteristics of the various types of insulation which are presented in Torok's paper have been obtained in the Trafford High-Voltage Laboratory. For the purpose of illustration in the discussion on application which fol-

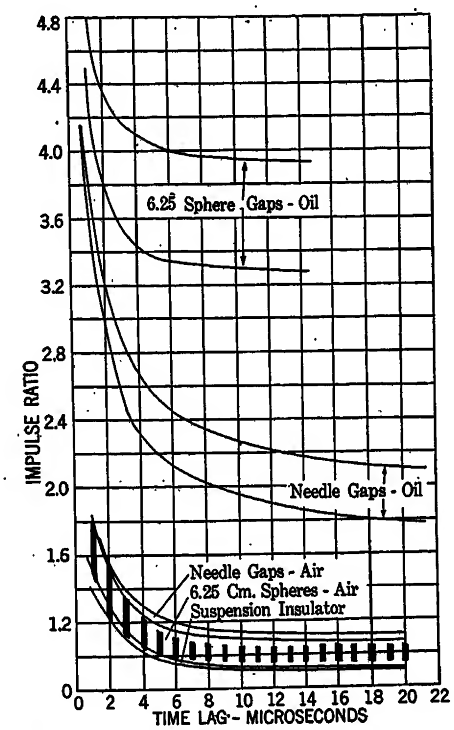

Fig. 4—Impulse Ratio Curves for Insulators and Spark-Gaps

Negative Terminal Grounded

lows, some of the curves are reproduced here. Fig. 4 shows the impulse ratio time lag of suspension insulators and needle-gaps in air. Fig. 5 shows the flashover voltage time-lag curves of suspension insulators with and without arcing rings and Fig. 6 shows the same information plotted in terms of impulse ratio. The work done in investigating the time-lag flashover characteristics of needle-gaps and sphere-gaps of various sizes at wide spacings in air is particularly important in connection with the determination of the best form of relief gap to be used in connection with the rationalization of the station insulation and the line insulation, in cases where it is not feasible to reduce the latter for a distance of one-half mile outside the station. It should be noted that the divergence in characteristics of needle-gaps in air for large and small gaps is extremely small. With spheres the

2. J. H. Cox and Edward Beck, *Cathode Ray Oscillograph Studies of Lightning on Transmission Lines*, Winter Convention A. I. E. E., 1930.

3. J. J. Torok, *Surge Characteristics of Insulators and Gaps*, Presented at the Winter Convention A. I. E. E., 1930.

divergence is larger. It will be noted in Fig. 4 that the divergence in impulse characteristics for suspension insulators in going from two-unit to 16-unit strings is extremely small. Fig. 7, which gives the data on suspension insulators drawn in a somewhat different manner, shows comparison of our Trafford laboratory data with laboratory data published by Peek,[4] which comprises the values he obtained with three types of wave; namely 5, 20, and 80 microsecond waves according to his definition.

Discussion of Flashover Time-Lag Characteristics

Let us now compare the characteristics of the impulse ratio curves for needle-gaps with those for insulators. It will be noted in Fig. 4 that the general shape of the curves is very similar, and that if the 60-cycle flashover point of the needle-gaps is reduced 12 per cent over that of the string of insulators, the voltage time-lag curves will practically coincide. The needle-gap will show a slightly greater time lag at the high voltages. In Fig. 6 it will be observed that the effect of the arcing rings is to

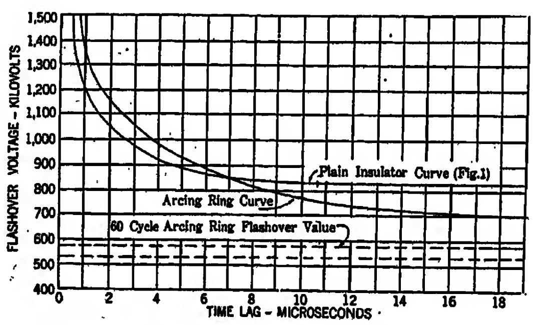

Fig. 5—Time-Lag Curve for 24-in. x 30-in. Arcing Rings

Nine No. 641 units; 43.5-in. spacing

very greatly increase the time lag for a given ratio of surge voltage above the 60-cycle flashover voltage. However, for a given string of insulators, the effect of the arcing rings is also to decrease the 60-cycle flashover as shown in Fig. 5. Consequently, the flashover voltage time-lag curve of the insulator string provided with arcing rings will cross that of the plain string somewhere in the neighborhood of eight microseconds; hence for waves that take more than eight microseconds to flash over the plain string, the string provided with arcing rings will have a shorter time lag, and will therefore flash over before the plain string, but for surges that take less than eight microseconds to flash over the plain string, the string provided with arcing rings will have a greater time lag, and therefore such a string will take a higher voltage to flash it over with the same time lag. Since about the longest time lag for a lightning wave to flash over an insulator string is 15 microseconds, in order to bring the impulse flashover strength of the two to equality at this point, the string provided with arcing rings would have to have its 60-cycle flashover raised in inverse proportion to the relative-value of the impulse ratio at this time lag.

It does not follow that because an insulator string provided with arcing rings and with its 60-cycle voltage raised so as to produce equal impulse strength at 15 microseconds has higher time lag for waves which flash over at less than 15 microseconds, it will result in lower outages on a line than the simple string. It is true that with lightning waves of short duration, this will be the case; but such lightning waves are not sufficiently numerous to be of any great consequence in determining outage factors. With high surges of long duration, the string provided with arcing rings will flash over just as frequently as the plain string. Considered from the point of view of the severity of the chopped wave which will pass an insulator after flashover, the insulator string provided with the arcing rings will be much worse than the plain string. Consequently, in the recommendations for reducing insulation in the neighborhood of stations, it is stated that the insulator string corresponding to the class of transformer used at the station shall be an unshielded string. Therefore, in rationalizing station insulating structures with the line, only plain insulator strings should be considered; or if shielded strings are used, the 60-cycle flashover should be sufficiently reduced so that the time lag at the higher surge is no greater than that of the plain string specified. It should be pointed out that the horn-gap, chosen to be used as a relief gap in cases where it is not practicable to reduce the line insulation, has a low 60-cycle flashover as compared with the corresponding insulator string. The reason also in this case is that in order to assure that the impulse strength of the gap will not be greater than the impulse strength of the corresponding insulating string at high voltages, it was necessary to use a low 60-cycle flashover, because the horn-gap has a relatively long time lag for high surges.

Proper Basis for Rationalization of Station Insulation and Transmission Line Insulation

Obviously, the station insulating structure should be rationalized wherever possible with respect to the transmission line and not with respect to any extraneous device such as the horn-gap, since the object is to insure that the station insulation will be at least as strong as the line insulators adjacent to the station so that if a flashover should occur, it will occur on a line and not on station apparatus. In contrast to the line flashover which occurs and is suppressed without damage, flashover in the station insulating structure may involve more than the particular structure which flashes over, and may result in serious damage to the station and a prolonged outage. Measurements have been made in the laboratory of the impulse ratio range of pillar type insulators, and it has been determined that this range is above that of suspension insulator strings; consequently, if at 15 microseconds the 60-cycle flashover of

4. F. W. Peek, Jr., *Progress in Lightning Research*, A. I. E. E. Quarterly Transactions, April 1929, p. 436.

the pillar type insulator is slightly higher than that of the insulator strings near the station, the pillar type insulator will be properly rationalized with respect to the transmission insulation. Other important insulating structures used in stations are outlet bushings which form part of circuit interrupters and transformers. The impulse ratio time-lag characteristics of bushings may be modified by proper terminal arrangements so that they will have the same flashover voltage time-lag characteristics as the insulator string over a range of 20 microseconds; and if the flashover voltage at each value of time lag is made 5 per cent higher than that of the transmission line insulators, the conditions of rationalization are satisfied.

With lightning arresters at the station, the necessity for rationalizing the insulating structures with the line is sometimes questioned, but cases have been known where a direct stroke at the station has resulted in destruction of the lightning arresters, in which case for subsequent operation,—until the arresters are replaced,—the station has to fall back on the impulse flashover of the insulators to limit the surge potential to which the apparatus is subjected. Furthermore, with lightning arresters it is not actually necessary to have the insulation of the adjacent portions of the line as strong as the rest of the line, for the reason that the protective effect of the lightning arresters extends for some distance. It may be assumed that with a lightning arrester properly chosen and of proper characteristics, no flashover will ever take place in the station insulating structures except with some exceptional condition such as a direct stroke of unusual magnitude; but even in such cases, with a modern station provided with proper overhead ground wire protection it is very unlikely that a direct stroke to the station will cause a flashover of the station insulating structures when the station is protected by adequate lightning arresters.

Lightning Arrester as Protection of Line Against Flashover

To understand the manner in which a lightning arrester protects insulating structures along the transmission line some distance from the point of installation, it is necessary to understand the action of a lightning arrester in protecting an insulating structure or piece of apparatus. When an incident surge strikes a lightning arrester of the valve type, the arrester at once discharges, and in so doing, produces a low resistance path to earth. In the true valve type arrester, the actual resistance of the path is extremely low, but the arrester itself has a counter e. m. f. equal to the glow or corona potential which, together with the resistance of the arrester, limits the crest value of the surge passing the arrester to a certain definite value. The action of breakdown, or short circuit, causes a negative wave which might be called the protective wave to flow along the transmission line in the opposite direction to the incident wave. This wave is equal to the difference between the wave that passes the arrester and the incident wave. As a result, if an insulating structure is distant from the lightning arrester at a length equivalent to one light microsecond, the insulating structure will have the full value of the surge impressed on it during the time the surge takes to reach the lightning arrester and the time the protective wave takes to reach the insulating structure; that is to say, two microseconds. Consequently, the insulating structure will have the full value of the surge for two microseconds, after which it will be reduced by the protective wave to a safe value. We may therefore say that the insulator string is protected from all waves that take more than two microseconds to flash it over. If the insulator or insulating structure is distant from the lightning arrester two light microseconds, then it will have the full wave impressed on it for four microseconds before the protective wave reaches it and it will therefore be protected against all surges that take more than four microseconds to flash it over. It follows that since the longest time lag in the flashover of an insulator due to a lightning surge is of the order of 15 microseconds, some measure of protection is obtained for transmission line insulators from lightning arresters located at stations for distances of more than one-half mile from the station. Consequently, the insulation of the transmission line can be graded for one-half mile outside the station without increasing the outage factor for this portion of the transmission line as compared to the rest of the transmission line. In fact the insulation could be graded down to the insulator string or structure which would be just protected by the lightning arrester at the station.

It will now be evident that the proposed rule to grade the insulation of the transmission line down for one-half mile outside the station is not purely an arbitrary decision, but has good theoretical basis because while the arrester is at the station, it is not necessary to have the full insulation at points near the lightning arrester in order to maintain the outage factor and if the arrester is absent for some reason it is essential as a back-up. Of course, at the station the outage factor with a properly designed and applied lightning arrester is zero, and at a short distance out from the station with the proposed reduced insulation, the outage factor becomes the same as that of the transmission line. From that point out to the end of the half mile distance, the outage factor will be somewhat greater, the average over the whole half mile being about the same as that of the line.

Protection of Transmission Lines by Means of Arresters

The impulse time-lag curves of transmission line insulators may be very usefully applied to the protection of transmission lines by means of lightning arresters. The range over which a lightning arrester will afford protection to a transmission line depends to a

great extent on the wave form of the surge. However, if we assume the most severe type of lightning surge, which is one that comes to its maximum in a relatively short time,—say not more than one microsecond,—and at the end of twenty microseconds has a value of not less than 75 per cent of the crest value, we find that the protection afforded by a lightning arrester may be quite simply estimated on the following basis. We shall divide the line into sections, approximately one microsecond light intervals from the arrester. Let us take a point three microseconds distant from the arrester and let us suppose that the surge approaches the arrester from the direction of this point; then this point will be subjected to the full value of the wave for three microseconds before it reaches the arrester. The action of the arrester, as we have indicated above, consists in absorbing part of the energy of the surge and reflecting the remainder so that the wave that passes the arrester is the difference between the actual wave and the reflected portion. It will be noted that if we take the energy of the portion that

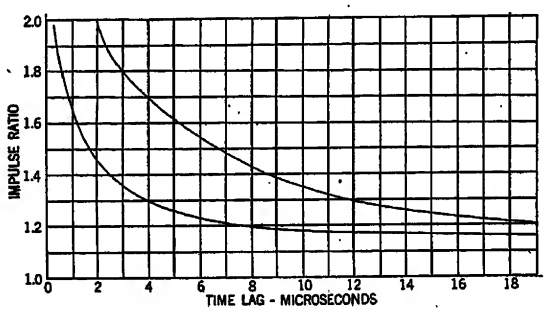

FIG. 6—IMPULSE RATIO CURVES FOR NINE SUSPENSION UNITS No.641 AND 24-IN. x 30-IN. ARCING RINGS

passes, plus the energy of the portion that is reflected, this will be less than the total energy of the incident wave; the difference between the two values is the energy absorbed by the arrester. This reflected wave will take three microseconds to reach the given point so that the total time during which this point is subjected to the full value of the wave is six microseconds. Let us now refer to Fig. 6; we find that with six microseconds given in the lower curve, the insulator string will have an impulse ratio of 1.23, and the conclusion is that all waves of this type having a crest value above 1.23 times the 60-cycle flashover of the insulator string will cause a flashover, and waves below this value will not cause a flashover. By using the probability curve of lightning surge occurrence in the manner discussed by H. L. Wallau,[5] we can estimate the probable reduction in outages at this point as a result of the presence of the lightning arresters placed three light microseconds from this point. If the lightning arresters are placed six light microseconds apart, this value will be the outage factor for the middle points between the lightning arresters. We may proceed with other points closer to the lightning arresters; for instance, consider the point two light microseconds from the arrester. This point would have the full wave for four microseconds which on the curve shows an impulse factor of 1.3 so that it would only flash over for waves 1.3 times the 60-cycle flashover value of an insulator string at this point. This, from the probability curve, will give a lower outage factor than the first point, and taking each insulator string in turn and the arithmetical average of the outage factors we obtain the outage factor of the line. It should be noted that for a surge coming from one direction, all the insulators on the farther side of the lightning arrester are protected from flashover; but this does not affect the actual outage factor, as this is also true of all methods of reducing the outage factor of transmission lines such as overhead ground wires.

RATIONALIZATION OF TRANSMISSION LINE INSULATION IN PROPORTION TO PROTECTION

Another way of applying the line type arresters is to equalize the outage factors by varying the insulation. The lightning arrester that is used in protecting a transmission line will have a cut-off voltage equal to the normal line voltage; the crest voltage will therefore be 2.0 to 2.5 times the line voltage. We may assume that if the crest value of the wave which remains after the arrester has functioned is impressed on the insulator string for more than 15 microseconds, it will just cause flashover. We therefore take 15 microseconds on the curve of Fig. 6, and find that the impulse ratio is 1.15. We therefore assume that the insulator string, in order to receive 100 per cent protection from the transmission line, must have a 60-cycle flashover equal to 2.2 times line voltage. On this basis, a 132-kv. line will require only five insulators at the arrester point. Let us assume that we wish to protect the point farthest from the lightning arrester from all waves which have a crest value less than 1500 kv. At six microseconds we have an impulse factor of 1.23, so that the 60-cycle crest value must therefore be 1500 divided by 1.23 or a root-mean-square value of 860 which would require a string of insulators of 16 units. For the insulator string two light microseconds away, the time lag is four microseconds and the impulse factor 1.3, which gives a 60-cycle flashover of the string of 815 kv. which will require 15 units. For the insulator string one light microsecond away, the time lag will be two, and the impulse factor will be 1.56 which requires an insulator string having 60-cycle flashover of 680 kv. This requires a string having 12 units. The average number of units will therefore be 13, and the system will be protected against all lightning surges of maximum severity below 1500 kv.

The above example has been based on practically square-topped waves. The actual protection for waves having slopes of two to three microseconds will be

5. H. L. Wallau, "Relative Frequency of Voltage Surges Induced by Charged Clouds," *Electric Journal*, August 1928.

much better. It has also been assumed that the string was a straight string without arcing rings. When arcing rings are used the protection is still further increased and fewer units may be used. For example, if strap type rings are used (Fig. 6) the impulse factor at 15 microseconds is 1.24 as compared to 1.15.

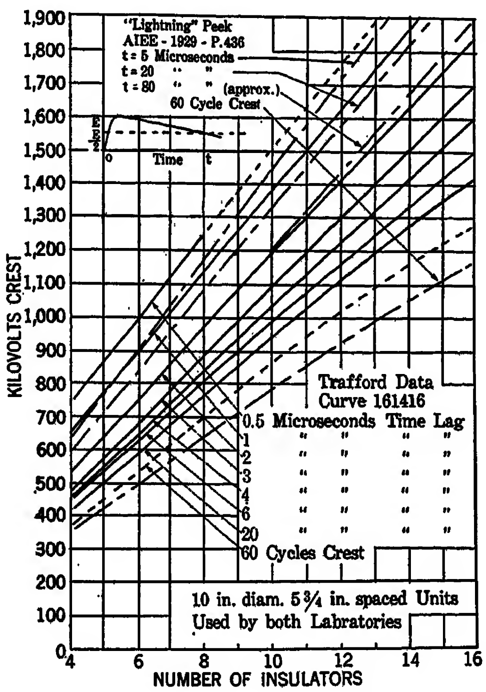

FIG. 7—COMPARATIVE SURGE DATA (GENERAL ELECTRIC COMPANY—WESTINGHOUSE ELEC. & MFG. CO.)

This would mean practically that the five-unit string would probably be satisfactory at this point. At the point three light microseconds away with strap type rings, we would have an impulse factor of 1.54 which corresponds to a 60-cycle flashover of 685 kv. with arcing rings, or a plain string flashover of 760 kv. which would therefore require 14 units instead of 16 with the plain string. At the point two light microseconds away the time lag is four microseconds and the impulse factor is 1.8 which gives a 60-cycle flashover of 590 for the string with strap rings corresponding to 670 for a plain string. This would require a string of 12 units. At the tower one light microsecond away we shall have a time lag of two microseconds and an impulse factor of 2.3. This gives a 60-cycle flashover of 460 kv. with arcing rings corresponding to 530 kv. for a plain string which requires a string of nine units. This gives an average length of string of less than 11 insulators.

This method of rationalizing the insulation in relation to the amount of protection it receives from the arrester gives the lowest outage factor for a given average length of string. It will be necessary, however, in practical construction work to consider other elements, such as the tower design, but it appears that by properly organizing the construction work several towers of different size could be used with an average cost of tower not appreciably greater than if flat insulation were used so a great reduction in actual outage factor due to lightning should be possible with little added cost. It should be remarked that the performance of the 132-kv. line, as has been indicated, would be better than that of a line without arresters having a flat insulation of 16 units. In other words, the arrester-protected line with graded insulation would give insulation superior to a line over-insulated with 16 units. It should be noted that in this case the arresters are placed seven light microseconds apart. With closer spacings, fewer insulators will be required for the same standard of protection. A curve may be plotted giving 60-cycle voltage or number of insulators against distance or light microseconds. Such a curve is shown in Fig. 8, illustrating the above example. With such a curve, the cost of arresters and insulators with different spacings of arresters along the line may be readily obtained.

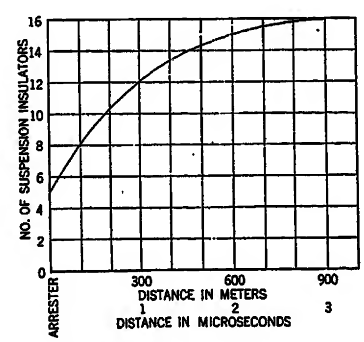

FIG. 8—CURVE SHOWING INSULATION REQUIRED AT VARIOUS DISTANCES FROM LIGHTNING ARRESTER FOR 132-KV. LINE FOR PROTECTION AGAINST A VOLTAGE OF 1500 KV.

Discussion

For discussion of this paper see page 1496.

The Effect of Transient Voltages on Dielectrics—IV

Law of Impulse Spark-over and Time Lag

Relative Effects of Different Wave Shapes—Comparison of Lightning Waves and Laboratory Waves—Coordination of Line Insulation

F. W. PEEK, JR.*

Fellow, A. I. E. E.

Synopsis.—The law of time lag and impulse breakdown is derived from experimental data. This law, which appears to be rational, shows that a given amount of energy is required to cause breakdown of a given gap and that voltage and time are interdependent. It is quite in accord with the work in the original paper and applies to breakdown on rectangular waves, on the front of slanting waves, or to overvoltages on standard waves.[1] By means of simple formulas the results for any wave can be calculated or the effects of different waves correlated.

Three general types of impulse tests, dependent on the form of wave used and the spark-over point selected, are discussed as follows:

1. The so-called "rectangular" wave with spark-over on the top

2. The uniformly rising voltage with spark-over on fronts of various slopes

3. The use of a "standard" wave of logarithmic front and tail with spark-over occurring at any desired point on it.

Method 3, using the full standard wave, is by far the simplest to apply and gives the most consistent results. It is also shown that it may be used in a way to give effects equivalent to the other two methods. Interesting energy relationships for impulse failures of gaps are brought out in this connection.

Field experience with actual lightning waves is compared to laboratory results with the "standard" wave and found to check very closely. A statistical study is described in this connection which now allows considering the lightning problem from an economic aspect.

The advantages of coordination of line and apparatus insulation are pointed out and the adaptability of the "standard" laboratory wave to such procedure is described.

* * * * *

I. Introduction

It is the object of this paper to discuss the relative effects of different forms of voltage transients on insulators, gaps, and insulation; to show how the effects and breakdown voltages of various types of transients are related; and to compare natural lightning waves with those used in the laboratory. Such knowledge is necessary in making a comparison of insulators, insulation, and in coordination. The law of impulse spark-over has been determined and formulas have been developed to predetermine time lag and breakdown voltage for the various types of transients.

When voltage is applied between electrodes in air or other gaseous insulation and slowly increased, breakdown eventually occurs. This is the minimum voltage that will cause failure for the given conditions. With a rapidly increasing voltage, breakdown does not take place when this minimum value is reached but the voltage rises to some higher value before failure occurs. A voltage higher than the minimum value is also required when the time of application is in any way limited. This follows because energy and therefore time is required to cause breakdown. The ratio of the impulse spark-over voltage to the minimum or continuously applied spark-over voltage is called the impulse ratio; the interval from the time the impulse reaches the continuously applied spark-over voltage until breakdown occurs is termed the lag and is conveniently measured in microseconds (millionths of seconds). The lag is not constant for a given arrangement but decreases with increasing rate of application of voltage. Thus breakdown is a function of both voltage and time. The shorter the time, the higher the voltage. There is a time lag for all types of electrodes but it is minimum for electrodes causing approximately uniform fields, such as spheres, and is a maximum for electrodes causing non-uniform fields, such as needle-gaps. For dissimilar electrodes, impulse spark-over takes place at the lowest voltage when the electrode in the denser field is positive. Accordingly, it follows that the impulse spark-over voltage of gaps and insulators is always higher than the continuously applied or 60-cycle voltage so that the impulse ratio is greater than unity. In general the impulse breakdown voltage for liquid and solid insulations is also higher than the continuously applied breakdown voltage.

The above paragraph is practically a quotation from the first paper on this subject (to which this paper may be considered a supplement).[1] The early results still obtain. Although when that investigation was made there was no oscillographic means of measuring waves of such short duration, the lags in millionths of seconds were determined as a result of calculations and indirect methods and the mechanism of breakdown was correctly pictured. Recent high-voltage research with the Du-

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

1. For references see Bibliography.

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four type of cathode ray oscillograph has simplified the problem and verified the early results.

II. Types of Impulse Tests

There are three general types of impulse tests, as follows:

1. Rectangular Wave. The rectangular wave method

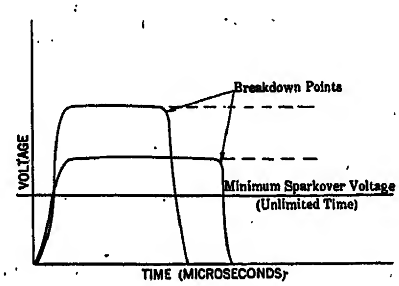


Fig. 1—Rectangular Form of Impulse Wave

is illustrated in Fig. 1. A theoretical rectangular wave would rise instantly to a given value and remain constant until breakdown occurred. However, such a wave can generally only be approximated in practise. Actually, about one-half microsecond is usually required to reach crest as illustrated in Fig. 1. This method is interesting theoretically but the waves are not typical of the usual high-voltage surges.

2. Uniformly Rising Voltage. Spark-over for a uniformly rising voltage is illustrated in Fig. 2. The time and voltage are indicated at spark-over. Note that when the minimum spark-over voltage is reached breakdown does not occur immediately because con-

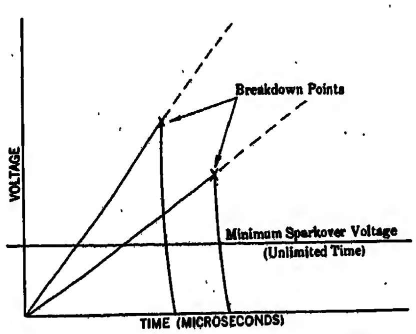


Fig. 2—Sparkover on Front of Waves of Various Slopes

siderable time is required at that voltage. The wave accordingly rises above this value. The more rapidly the voltage is applied, the higher the breakdown voltage is, and the less the lag. This is a condition that occurs in practise when the lightning voltage is much higher than the breakdown value of the insulation and spark-over occurs on the front.

3. Standard Wave of Fixed Shape. In this method a fixed or standard wave of the form shown in Fig. 11 is used and there are several ways in which the test may be made.[1,2] By the proper application of this method the whole range of breakdown effects caused by the rectangular wave, the uniformly rising voltage or any other wave can be obtained. The two general methods are:

a. Full-Wave Method. The given wave is applied and the voltage is gradually increased until spark-over occurs on 50 per cent of the applications. Breakdown is then taking place on the tail as shown in (*a*) Fig. 3. Since the voltage is just high enough to cause sparking, the full wave is utilized. This method gives the most reliable and consistent results and is the simplest to carry out. The only measuring device necessary is a parallel sphere-gap which gives accurate results where the full wave is used.

b. Overvoltage Method. This is the same as the above except that an overvoltage is applied which may be any given percentage in excess of the full wave value.[1,2] The time of spark-over at (*b*) may be measured by a cathode ray oscillograph. Either a short or long wave may be used as shown in Fig. 3. The standard wave overvoltage method (with long wave) has been compared with, or described as a rectangular

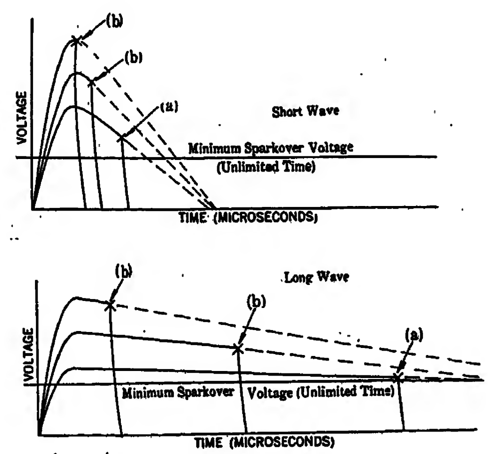


Fig. 3—Sparkovers on Tails of Short and Long Waves

wave method with steep front and horizontal top. However, the two methods do not give the same results.

III. The Effects and Relative Breakdown Values of Various Types of Waves—Law of Impulse Spark-Over and Time Lag

The effects and relative breakdown values of the various types of waves will now be discussed in more detail.

1. Rectangular Wave. An investigation with this type of wave is of theoretical interest. If the front could be made perpendicular and the top horizontal, two variables would be eliminated. However, it is not practical to accomplish this and in general it is difficult to produce a front reaching maximum in less than one-half microsecond. It is thus the same as any other fixed in this respect, is more difficult to obtain and is sensitive to changes in front.

Oscillograms of such a wave with one-half microsecond front are shown in Fig. 4. The results of insula-

tor spark-over voltages are given with impulse ratio in Fig. 5. It is seen that the values for the various lengths of insulator strings fall well on this curve. This impulse ratio-time curve has particular interest because it seems to offer a means of correlating the

FIG. 4—OSCILLOGRAM OF SPARK-OVER OF POINT-GAP WITH RECTANGULAR WAVES OF DIFFERENT VOLTAGES

spark-over values of different waves. This follows because these curves follow the equation

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right) \qquad (1)$$

$$\beta = \text{impulse ratio} = \frac{e}{e_0}$$

t = time lag in microseconds

a = a constant (under certain conditions a may vary; it may be necessary to add a factor depending upon the spacing)

when β and a are known, the lag can be calculated:

$$t = \left(\frac{a}{\beta - 1}\right)^2 \qquad (2)$$

The impulse spark-over voltage is

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right) \qquad (3)$$

where e_0 is the continuously applied breakdown value.

For convenience in practical application, the 60-cycle crest spark-over value has been taken as e_0. If the impulse ratio is known, the impulse spark-over value is then found by multiplying β by e_0. For certain dissymmetrical electrode arrangements the spark-over voltage may be materially lower when the non-grounded electrode (or the one in the denser field) is positive. For a theoretical study it would in such cases be preferable to use the corresponding (+) and (−) direct current, e_0 voltages. This would tend to bring the (+) and (−) impulse ratios more nearly together since both the impulse spark-over voltage and the continuously applied spark-over voltage are affected in the same way by polarity.

This equation is of further interest because it appears to be rational. In the original paper on this subject it was pointed out that energy, and therefore voltage and time, were necessary to rupture insulation.[1]

It may be assumed that a given amount of energy is necessary to break a given gap. This requires a definite ionization apparent as corona and corona loss. Corona loss, according to the quadratic law, is:

$$p = (e - e_0)^2\, k$$

For the rectangular wave the energy may be expressed

$$w = (e - e_0)^2\, k\, t$$

or

$$\sqrt{w} = (e - e_0)\sqrt{k\,t}$$

$$e - e_0 - \sqrt{\frac{w}{k\,t}}$$

$$e = e_0 + \sqrt{\frac{w}{k\,t}}$$

$$e = e_0\left(1 + \sqrt{\frac{w}{e_0^2\,k\,t}}\right)$$

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

where $$a^2 = \frac{w}{k\,e_0^2} = \frac{w}{k_1\,l^2}$$

l = length of gap

When the impulse ratio is constant, a is constant and it then follows that w varies as the square of the e_0 voltage or approximately as the square of the gap length. This also follows when β is constant with

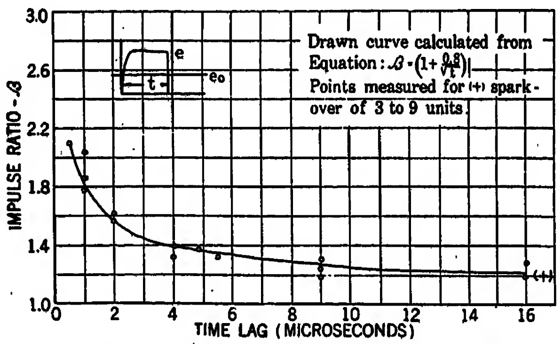


FIG. 5—IMPULSE RATIO-TIME LAG CURVE OF INSULATOR SPARKOVER WITH RECTANGULAR WAVE OF ½-MICROSECOND FRONT

(Standard 5¾-in. spacing—10-in. diameter insulators)

varying gap length in the case of the fixed wave. (See Figs. 9 and 16.)

Thus

$$\frac{e}{e_0} = \left(1 + \frac{a}{\sqrt{t}}\right) = \beta$$

The drawn curve in Fig. 5 was plotted from the equation

$$\beta = \left(1 + \frac{0.8}{\sqrt{t}}\right)$$

Similar results are obtained for needle-gaps, etc., with different values of (a); a is usually higher when the electrode in the denser field is $(-)$. The author has checked this law on other data and it seems to apply.[5]

2. Breakdown on Uniformly Rising Voltage. Breakdown or spark-over on the front of a uniformly rising voltage is illustrated by the oscillogram in Fig. 6. While the sphere-gap has very little time lag, and is quite accurate for measuring the crest voltage of a full wave, it is not always sufficiently accurate to measure the breakdown voltage on a very steep front. The error in time and voltage will vary but may be of the order of 10 per cent low if correction is not made. Oscillographic measurements or sphere-gap corrections

A

B

FIG. 6—OSCILLOGRAMS SHOWING SPARK-OVERS ON FRONTS OF IMPULSE WAVES

(a) Spark-over of point-gap:
(b) Spark-over of insulators: A. Complete wave
B. Spark-over of 5 units
C. Spark-over of 3 units

should therefore be made for every point when this method is used. The sphere-gap is also subject to correction for polarity for the larger spacings. This correction, which may be opposite the point-plane effect, becomes of importance when it is desired to determine a small $(+)$ and $(-)$ difference on other gaps.

The results of tests on insulators and point-gaps are given in Figs. 7 and 8. It will be noted that for any given time for breakdown the impulse ratio is practically constant and for a wide range of the length of string or gap. Any difference in impulse ratio with length or number of units usually becomes appreciable only for short spacings. The same general law connecting voltage and time lag applies for breakdown on the rising front as for the rectangular wave. For suspension insulators it is:

$$\beta = \left(1 + \frac{.9}{\sqrt{t}}\right)(+)$$

$$\beta = \left(1 + \frac{1.2}{\sqrt{t}}\right)(-)$$

The difference between $(+)$ and $(-)$ for insulators

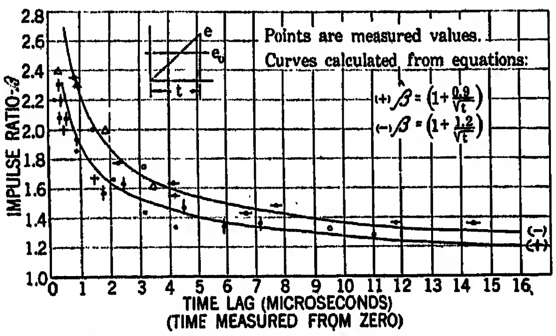


FIG. 7—IMPULSE RATIO-TIME LAG CURVE OF INSULATOR SPARKOVER ON FRONT OF WAVE

(Standard 5¾ in. spacing—10 in. diameter insulators)

represents a range rather than a definite division, with $(-)$ maximum high and $(+)$ minimum low. Individual $(+)$ values of β may be approximately 5 per cent

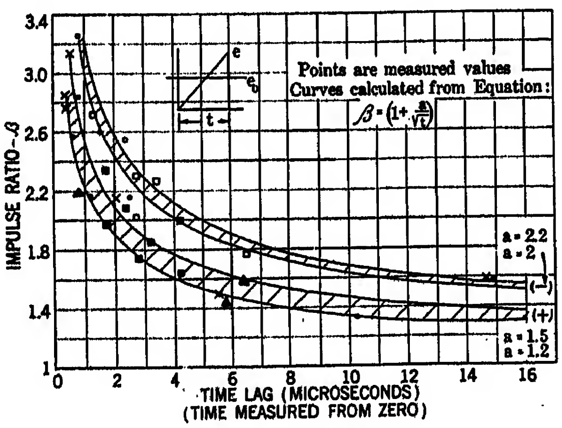


FIG. 8—IMPULSE RATIO-TIME LAG CURVE OF POINT-GAP SPARK-OVER ON FRONT OF WAVE

higher than the calculated and $(-)$ values 5 per cent lower.

For point-gap

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right)$$

where a = 1.2 to 1.5 $(+)$ and a = 2.0 to 2.2 $(-)$ depending upon the type of gap. The lower $(+)$ curve approaches a point-plane condition which gives the minimum spark-over.

For spark-over on the front, time, t, has been taken

for convenience from zero to breakdown. However, this requires some explanation since the effective time of corona formation, $(t - t_0)$ in Fig. 2, is different from that for the rectangular wave. In this case the voltage is not constant but is a function of time so that the expression for energy loss following the quadratic law is

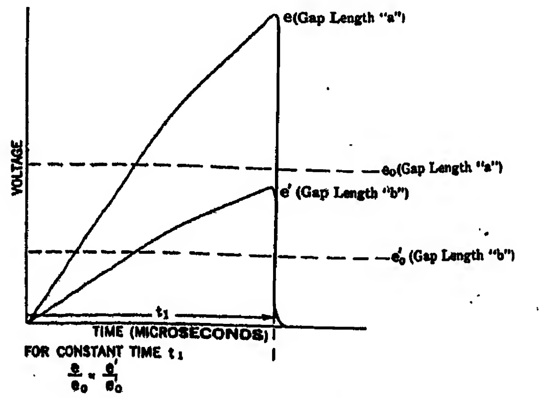


FIG. 9—SPARK-OVER ON FRONT OF WAVE WITH CONSTANT TIME LAG

more complicated than for the rectangular wave as given above. It is

$$w = \int_{t_0}^{t} (e - e_0)^2 \, d\, t = \int_{t_0}^{t} (e_0 \, \delta \, t - e_0)^2 \, d\, t$$

which reduces to

$$(\beta^3 - 3\,\beta^2 + 3\,\beta) = \left(3\,\delta \frac{w}{e_0^2} + 1\right)$$

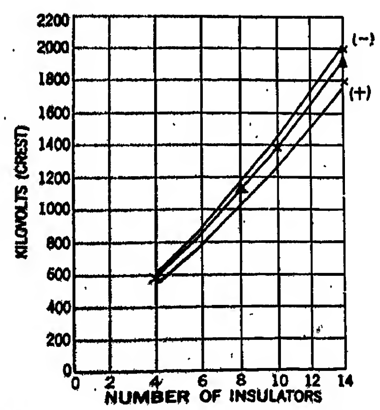


FIG. 10—COMPARISON OF SPARK-OVER VOLTAGES OF SUSPENSION INSULATORS WITH BREAKDOWN ON FRONT OF UNIFORMLY RISING WAVE IN TWO MICROSECONDS AND ON TAIL OF ½/5 STANDARD WAVE (50 PER CENT SPARKING)

Crosses (×) indicate spark-over values from natural lightning
Two microseconds (time-zero to spark-over)
½/5 Standard wave (from Fig. 12)—average
Two microseconds (time-zero to spark-over)

where

w = rupturing energy of gap
e_0 = minimum spark-over voltage (unlimited time)
δ = slope factor
β = impulse ratio

It can be shown that this expression gives equivalent results to Equation (1), particularly for small values of t, where diffusion losses during breakdown do not appreciably affect the energy. Equation (1) more closely follows measured values. The tests show that for a given type of gap or insulator the ratio $\frac{e}{e_0}$ remains approximately constant with change in gap length for a constant t. This is illustrated in Fig. 9. Since the rate at which a voltage rises is

$$\alpha = e\,/t = \text{kv/m. s.}$$

the spark-over voltage for any given β can be calculated.

Curves calculated by Equation (1) for spark-over on the rising front for insulators are given in Fig. 10, for (+) and (−) waves and for spark-over times t of 2 microseconds. The crosses show measured spark-over voltages for natural lightning on transmission lines. Note that the two microsecond curve on the rising front corresponds approximately to the ½/5 microsecond* wave of Fig. 12.

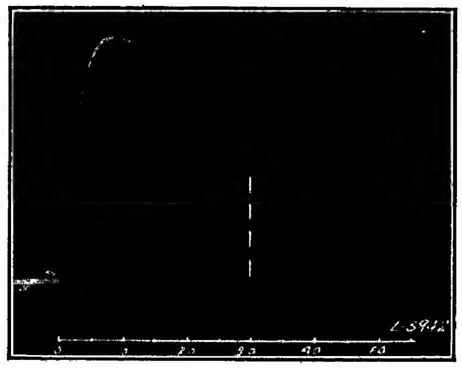


FIG. 11—OSCILLOGRAM SHOWING SPARK-OVER ON TAIL OF WAVE

Insulator spark-overs on transmission lines frequently occur on the rising front of the wave. It is, therefore, a practical condition.

3. Breakdown on the Standard Wave. Breakdown on the tail or crest of a fixed wave is illustrated in Fig. 3. The front is taken as the time from zero to crest and the length as the time from crest to half voltage on the tail; it is a convenient means of designating the wave. This method, using the full wave, has been most useful in comparing the lightning strengths of different types of gaps, insulators, and insulation. The test is very simple to make and good results can be obtained, as already noted, without the cathode ray oscillograph. The general method is to apply successive waves of increasing crest values until spark-over occurs on 50 per cent of the applications. An oscillogram illustrating this method is given in Fig. 11. Spark-over

*In this expression, which will be used for designating standard waves, the first number signifies front, while the second signifies time from crest to one-half voltage on the tail. Thus, ½/5/(+) means ½ microsecond front, 5 microsecond tail, and positive polarity on the non-grounded electrode. This method of designating was first suggested by K. B. McEachron.

curves are given in Figs. 12 and 13. Full line curves represent values for transmission line conditions. The crosses give natural lightning spark-over voltages measured on transmission lines. Note that the effects are closely approximated by the standard ½/5- and ½/20-microsecond waves. These curves are the average of (+) and (−) spark-over values.* Fig. 14 records the results of tests of insulators and point-gaps in parallel. The gaps were adjusted for equal sparking on points and insulators. The waves used cover an impulse ratio range of 2 to 1.2 and unity at 60 cycles. Practically the same relation between insulators and points holds throughout the range.

When a fixed wave is used, the ratio $\frac{e}{e_0}$ is approximately constant over a large range of lengths of a given

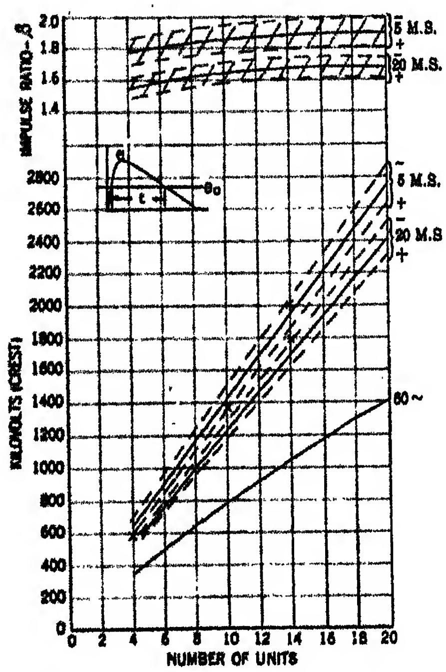


FIG. 12—SPARKOVER VOLTAGES OF SUSPENSION INSULATORS WITH "STANDARD" WAVE—50 PER CENT SPARKING

(Standard 5¾-in. spacing, 10-in. diameter insulators). The full curves should be used for transmission line conditions

gap or insulator string. This applies particularly for the longer gaps. Fig. 10 shows that the same effects can be obtained with the full wave as with sparking on the rising front; it is a matter of making the proper selection. However, the fixed wave method is much more satisfactory for practical tests.

A very wide range of impulse ratios can be obtained with a fixed wave by making the partial sparking test using the full wave, and also by applying voltages in excess of this value or overvoltages so that spark-over takes place nearer the crest as illustrated in Figs. 8 and 15. These tests can be made at 50 per cent sparking (that is, the full-wave method) and also at a given percentage of voltage above this value. For a given percentage of overvoltage on a fixed wave the impulse ratio $\frac{e}{e_0}$ is practically constant over a wide range of gap setting or insulator lengths, as illustrated in Fig. 16. The time lag t, for the different overvoltages can be plotted with the impulse ratio as in Figs. 17 and 18. When this is done it will be found that the voltage and

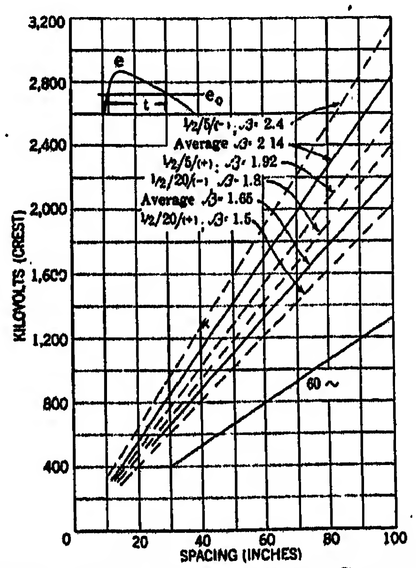


FIG. 13—SPARK-OVER VOLTAGES OF POINT GAP-WITH STANDARD WAVE—50 PER CENT SPARKING

The full curves represent transmission line conditions. The lower (+) curves approach a point-plane arrangement

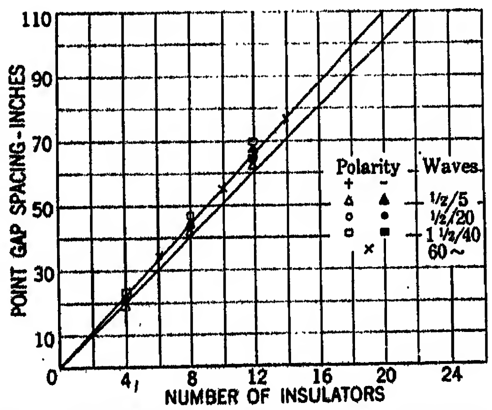


FIG. 14—CURVES SHOWING RESULTS OF PARALLEL TESTS ON STANDARD SUSPENSION INSULATORS

(5¾-in. spacing—10-in. diameter) and point-gaps, made to determine equivalent sparkover values. Curves represent range between 60-cycle and ½/5-microsecond waves

impulse ratio for relatively long and steep waves can be expressed by

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right)$$

or

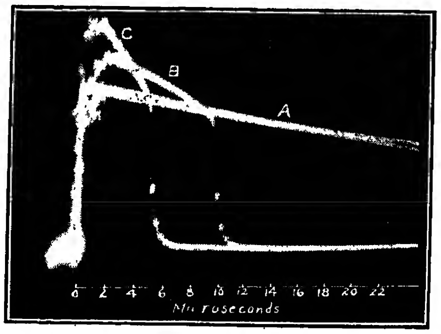
$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

*These curves differ somewhat from the original 5- and 20-microsecond curves because the original curves were based on a ¼-microsecond front while these are for ½-microsecond front.

where e_0 = 60-cycle spark-over (crest)
t = time above 60-cycle spark-over voltage

The expression applies for values of t less than approximately

$$\frac{(\beta - 1)\, c}{\beta}\, l \tag{4}$$



A

B

FIG. 15—OSCILLOGRAMS ILLUSTRATING OVERVOLTAGE EFFECT WITH STANDARD WAVE

(a) High-voltage bushing test:
A. Applied wave
B. Spark-over with 20 per cent overvoltage
C. Spark-over with 40 per cent overvoltage
(b) Bushing test with slight overvoltages

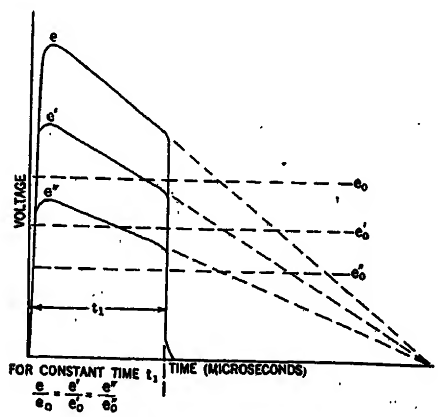


FIG. 16—OVERVOLTAGE SPARK-OVERS ON STANDARD WAVE AT CONSTANT TIME LAG

where c varies between 1 and 2 and depends upon the "50 per cent sparking" breakdown point and l is the length of the wave as defined above. When this lag is reached the full effect of the wave is utilized. This follows because the impulse voltage then approaches the 60-cycle value. This is illustrated as the 50 per cent sparking voltage in Figs. 17 and 18. When β is known for 50 per cent spark-over on the full wave (Table II), t may be calculated from (4). By substituting this value of t and β in (1), a is found. The impulse ratio and sparking voltage for the given wave on

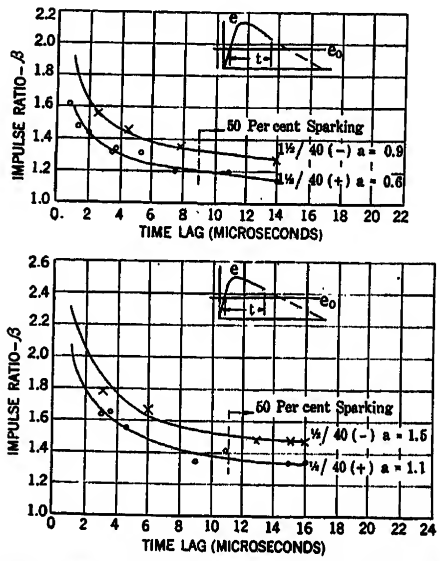


FIG. 17—IMPULSE RATIO-TIME LAG CURVES FOR OVERVOLTAGE SPARK-OVERS OF INSULATORS ON STANDARD WAVE

(Standard 5¾-in., 10-in. diameter insulators)

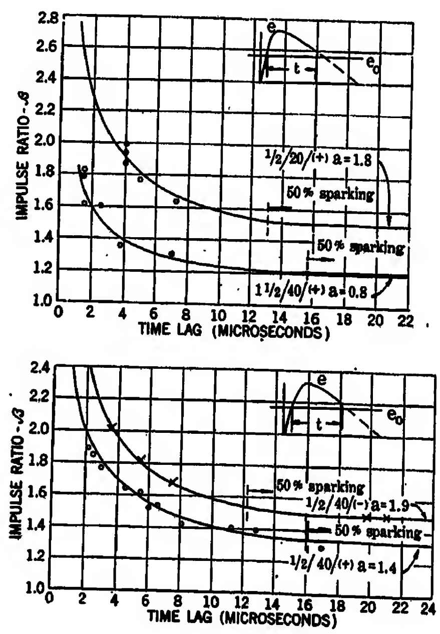


FIG. 18—IMPULSE RATIO-TIME LAG CURVES FOR OVERVOLTAGE SPARK-OVERS OF POINT-GAP ON STANDARD WAVE

overvoltages can then be calculated from (1) and (3).

The effects of various wavelengths and wave fronts for the full wave are given in Figs. 19 and 20. Fig. 21 shows the effect of varying front with constant length. These curves with constant length and varying front may be expressed by Equation (1) with t = front of

wave. The (+) and (−) curves in Figs. 17 to 21 represent a range in values rather than a definite division, the (−) curve representing maximum (−) values and the (+) curves minimum (+) values. Frequently the average (+) and (−) values are not far apart.

The cathode ray oscillograph was used in making all

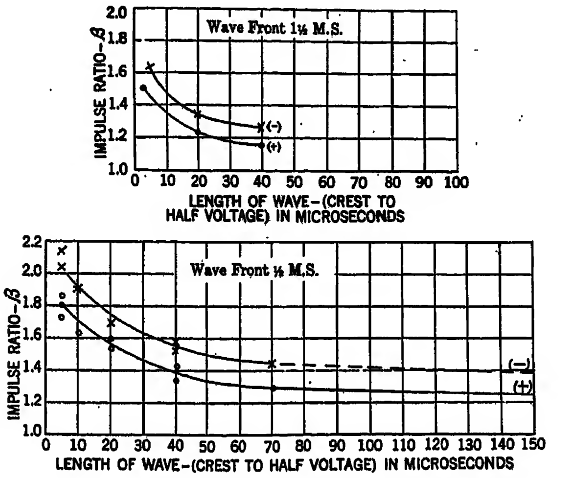


Fig. 19—Impulse Ratios for Full-Wave Insulators Spark-overs

(50 per cent sparking) with standard waves of constant front and varying lengths. (Standard 5¾-in., 10-in. diameter insulators)
Example—β = 1.8 for ½/5/(+)—To find impulse spark-over, multiply 60-cycle crest voltage by β.

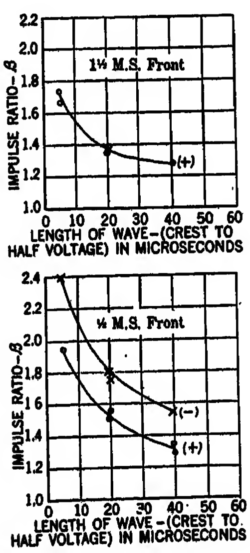


Fig. 20—Impulse Ratios for Full-Wave Point-Gap Spark-overs (50 Per Cent Sparking) with Standard Waves of Constant Front and Varying Length

tests. The sphere-gap was used for making calibration of the maximum of the full wave value used.

Values of a for different waves are given in Table I. Accurate values of β for various waves and overvoltages can be calculated by inserting the proper value of a in the formula. The full wave spark-over voltages can be calculated for various waves from β from Table II. Very

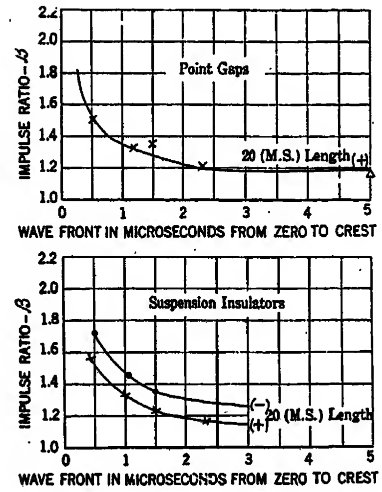


Fig. 21—Impulse Ratio-Time Curves of Point-Gap and Insulator Spark-over Showing Effect of Variation of Wave Front with Constant Wavelength (in this Case 20 Microseconds Effective Duration, *i. e.*, Above Half Voltage)

TABLE I
a FOR VARIOUS WAVES

Wave	Insulators		Points	
	(+)	(−)	(+)	(−)
Overvoltage				
½/40	1.1	1.5	1.4	1.9
1½/40	0.6	0.9	0.8	
Rectangular ½ microsecond front	0.8	....	....	....
Slanting	0.9	1.2	1.2	2.0
	....	....	1.5	2.2

(+) and (−) values represent a range

TABLE II
FULL WAVE SPARK-OVER
Impulse Ratio

Wave	Insulators		Points	
	(+)	(−)	(+)	(−)
½/5	1.75	1.95	1.92	2.4
1 /5	1.50	1.65	....	....
1½/5	1.46	1.58	....	....
3 /5	1.28	1.34	....	....
¼/20	....	....	....	....
½/20	1.58	1.7	1.5	1.8
1 /20	1.33	1.40	....	....
1½/20	1.25	1.33	....	....
3 /20	1.15	1.20	....	....
½/40	1.40	1.50	1.33	1.55
1 /40	1.22	1.30	....	....
1½/40	1.18	1.28	....	....
3 /40	1.10	1.15	....	....

The (+) and (−) values of β represent a range with minimum (+) values and maximum (−) values. Individual (+) values may be 5 per cent higher and (−) values 5 per cent lower than the curve. Frequently the average difference between (+) and (−) may be negligible. The average range between (+) and (−) for insulators in the table is 6½ per cent; for point-gaps it is somewhat higher.

extensive data on a and β have been obtained. As soon as these data are in form, the above tables will be revised and extended.

4. Law of Impulse Spark-Over for Oil and Solid Insulation. Equation (1) above applies for oil insulation and also seems to apply for solid insulation. However, the factor a must be properly evaluated.

IV. Comparison of Laboratory and Observed Natural Lightning Waves—A Statistical Study of Lightning Effects

1. Laboratory and Natural Lightning Waves. In the early work with the lightning generator it was necessary to decide on some wave or waves which would have the effects of the average severe lightning on insulators, insulation, and apparatus. This decision was necessarily based on theoretical considerations with the help of the meager experimental data on natural lightning that were then available. Research was made over a very wide range of wave-shapes with spark-over occurring on the fronts and tails. As tentative standards two waves were decided upon for general testing and comparison of insulators, and insulation—that is, the 5 and the 20 microsecond waves. These waves reach crest in ½ microsecond, decrease to half voltage in 5 and 20 microseconds, and to zero in 10 and 40 microseconds respectively.* Insulator spark-over curves obtained with these waves in the laboratory are given in Figs. 12 and 13. The crosses on Fig. 12 are points obtained by surge voltage recorder measurements of insulator spark-overs caused by natural lightning. These points fall in between the 5 and 20 microsecond curves. A further check is seen on the gap spark-over in Fig. 13. Other measurements on failures of insulators and insulation give impulse ratios of the order of 1.6 to 2. In obtaining the values in Figs. 12 and 13 the full wave was used by increasing the impulse voltage until spark-over occurred in 50 per cent of the applications.

TABLE III
PARALLEL SPARKING

Insulator Units	Point-Gap Setting (Inches)					
Wave	½/5		½/20		1½/40	
	(+)	(−)	(+)	(−)	(+)	(−)
4	20	22	23	22.7	23	21
8	43.5	44	45.2	46	47	46.5
12	64	70	70	71.2	70.2	69.2

Point gap set for equal sparking with parallel insulator.
Variation—plus or minus 5 per cent.

Data from some of the natural lightning waves measured by the cathode ray oscillograph are given in Fig. 22. The estimated front of the maximum voltage at the point of origin, and before the wave is free, as explained below, is given by the dotted line (b). It is this value that should determine the spark-over. Typical measured natural lightning waves are shown in Fig. 23 with the laboratory waves. These waves, in general, produce the same effects on lines and apparatus as the laboratory waves. *It is probable that insulator spark-overs frequently occur on the rising front of the wave as illustrated in Fig. 2.* If the waves were not chopped

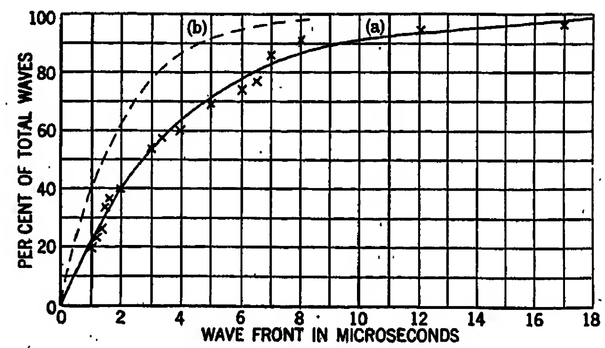


FIG. 22—PERCENTAGE OF LIGHTNING WAVES OF VARIOUS FRONTS MEASURED ON TRANSMISSION LINES

(a) Curve showing fronts of 35 highest natural lightning waves (voltage V_1) measured on Wallenpaupack-Siegfried Line in 1929
(b) Estimated equivalent fronts (voltage V) at points of origin of corresponding waves on curve a

the voltages would go much higher. Figs. 7 and 8 show how the impulse ratio varies with time on typical gap and line insulator arrangement.

Over one hundred oscillograms have been obtained of traveling voltage waves due to lightning on transmission lines. These waves had generally come a considerable distance and were thus greatly reduced in voltage, modified to some extent by attenuation, reflections, etc. In most cases they were evidently caused by storms

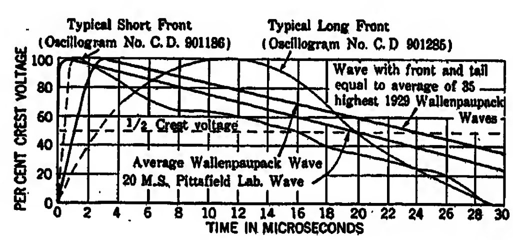


FIG. 23—TYPICAL NATURAL LIGHTNING WAVES OF LONG AND SHORT FRONTS, AND AVERAGE SHAPE AS RECORDED AT WALLENPAUPACK IN 1929

Pittsfield Standard 20-microsecond wave included for comparison

some distance away. It is interesting to examine these waves with the view of determining just what impulse spark-over voltages should be expected. The importance of this is seen when it is remembered that surge voltage recorder measurements indicated that lightning spark-over voltages were usually 1.8 or more times the 60-cycle voltage (see Figs. 12 and 13) although it is known that the impulse ratio varies widely with different waves and is dependent on conductor polarity. To

*Originally a ¼-microsecond front was used with a slightly higher voltage.

make this examination complete it is necessary to see what happens at the point of origin of the wave where the induced voltage V is maximum.

The formation of induced voltage on lines is as as follows:[4]

The charging process of the cloud is relatively very slow. This permits the leakage from line to ground of the charge having the same potential as the cloud. A bound charge opposite in potential and varying in intensity with the cloud charge is held on the line. The cloud discharges at a very rapid rate releasing the charge on the line. *The voltage from line to ground increases rapidly to a maximum value.* Eventually two free traveling waves are formed and propagated in opposite directions with voltages less than maximum. If the discharge were instantaneous the maximum voltage would be:

$$V = g\,h$$

while the maximum voltage of the free traveling waves would be:

$$V_1 = \frac{g\,h}{2}$$

Since the discharge is not instantaneous these two voltages are:

$V = g\,h\,\alpha$ (maximum actual voltage)

$V_1 = g\,h\,\alpha'$ (voltage of traveling wave)

where α and α' depend upon the time it takes the cloud to discharge and the distribution of bound charge. If this time is over a few microseconds, V and V_1 become quite small (see Fig. 24). From the above, insulator spark-overs should take place under the center of disturbance where the voltage is highest. They should thus be due to the voltage V, and not to the voltage V_1 measured by the oscillograph. Accordingly, the next step is to get an approximate idea of wave V from V_1.

Calculations for a range of cloud sizes and rates of discharge show that V reaches maximum in from one-half to one-third the time indicated by the front of the free traveling wave, and perhaps even less. Thus, voltage is applied at a more rapid rate for V than V_1. Therefore the impulse ratio for spark-over on the front should be higher for V than for V_1.

An examination of Fig. 22 shows that for the measured traveling waves 50 per cent reach crest voltage V_1 in less than 3 microseconds and 90 per cent in less than 8 microseconds. However, the rise in voltage V at the origin should be at least twice as steep as V_1 the impulse ratio at the origin should thus correspond very approximately to the dotted curve in Fig. 22. This shows that 50 per cent reach crest in less than 1½ microseconds and 90 per cent reach crest in less than 4 microseconds. On Fig. 7 are plotted impulse ratio curves for spark-over on the rising front of a wave with time. This shows that for the waves measured the impulse ratio for V should be higher than the average 1.55 for 90 per cent of the waves and over 1.9 for 50 per cent. These measurements thus seem to check the former impulse ratios obtained by surge voltage recorders of natural lightning in Figs. 12 and 13 and also justify the laboratory values of lightning voltage given in these figures. Of course, occasionally conditions may be right for breakdown to occur on the tail of the wave at a lower impulse ratio.

Fig. 24 shows that voltages high enough to cause spark-over by induction cannot occur unless the cloud discharge is quite rapid. For example, consider a line 30 ft. high and a cloud 2000 ft. long. For a discharge time of ten microseconds the maximum voltage $V = g\,h\,\alpha = 100 \times 30 \times 0.25$ (see Fig. 24) $= 750$ kv. With a 2000-ft. cloud and a 10-microsecond discharge the front would be in the order of 2 or 3 microseconds. The impulse ratio would be about 1.6. Thus V would not be sufficient to cause spark-over on 7 insulators, the standard for a 110-kv. line. It would thus appear

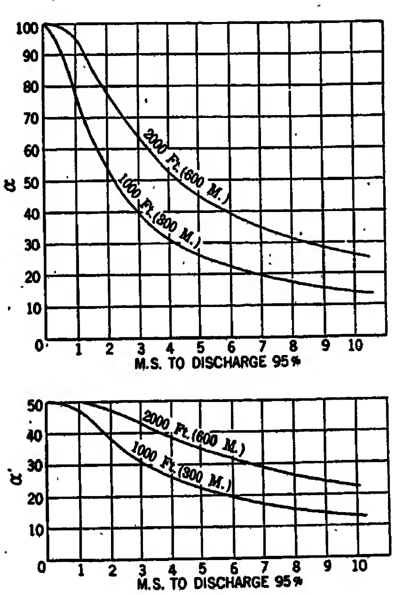


Fig. 24—Reduction Factors α and α' for Clouds of 1000- and 2000-Ft. Lengths

that voltage waves in Fig. 22, Curve (*b*) for a front of more than 3 microseconds (6 on the free wave) need not be considered *for high-voltage lines*. *For low-voltage lines* slower waves may reach sufficient voltage to cause spark-over at a lower impulse ratio. However, where the rate of cloud discharge is rapid, high induced voltages result. For example, assume a line 40 ft. high and a cloud 2000 ft. long discharging in 4 microseconds.

From Fig. 24, $\alpha = 0.53$

$V = 100 \times 0.53 \times 40 = 2120$ kv. This would give a wave with a front of about 2 microseconds at the source or 4 microseconds as measured when traveling free. The impulse ratio for the 2-microseconds front from Fig. 7 is about 1.8. With this impulse ratio the spark-over voltage is about 1900 kv. for 14 units from Fig. 10. Under these conditions the induced voltage is high enough to cause spark-over on a 220-kv. line.

This wave would correspond approximately to the average Wallenpaupack wave in Fig. 23. Induced spark-over voltages of a high impulse ratio would thus be expected for high-voltage lines and spark-overs at lower impulse ratios would be expected on lines insulated for voltages below 110 kv. Corresponding impulse ratios would also be expected for full wave and for "overvoltage" spark-over on the tail of the wave. For example, the average steep wave from Fig. 23 is 1/10 while the average for all high-voltage waves is 3/24. Overvoltages of from 0 to 50 per cent on these waves would give the highest impulse ratios observed.

It would thus appear that with reasonable assumptions as to length of bound charge (for example, 2000 ft.) and rate of cloud discharge, the average measured wave in Fig. 23 can be accounted for by induction and maximum voltage values of over 2000 kv. can be expected.

In case of direct strokes the wave would probably be still steeper and thus give impulse ratios over 1.8. Direct strokes become of relatively more importance as a cause of spark-overs as line insulation is increased or on the higher voltage lines.

While the above analysis can only be approximate, it is still probably accurate enough for its purpose.

A comparison of Figs. 10, 12, 13, and 14 shows that the standard waves of 5 and 20 microseconds can produce all the effects of breakdown on a rising front and offer a practical method of testing. Under equivalent conditions of time from Equation (1) the same spark-over results are thus obtained for the standard wave with breakdown on the tail (50 per cent sparking) and for uniformly rising waves with sparking on the front.

Fig. 14 shows how a range in impulse ratio varying from 2 (with the ½/5-microsecond wave) to 1.2 (with the 1½/40-microsecond wave) can be obtained with fixed waves for a check on coordination.

2. Insulation. The insulator or needle-gap is a useful means of expressing the strength of apparatus or insulation, especially when it is desired to compare test values obtained on waves of different shapes. By measuring the strength of insulation with insulators or needle-gaps the effect of wave variation is largely eliminated. See Fig. 14 where the point-gap is expressed in terms of insulator units.

3. Statistical Study. Fig. 25 is of particular interest since it is an attempt to arrive at the nature of lightning waves and voltages purely from a statistical study of outages. It is a plot of outages per hundred miles of line with the number of insulators per foot of line height. This method was used to put lines of different height and insulation on an equal basis. The points from lines in different parts of the country are shown on the curve. They were obtained on lines of varying height, number of insulators, with and without ground wires, etc., and are weighted and reduced to 100 thunder storm days per year. A word of explanation of Fig. 25 may be necessary. For example, referring to the curve with 0.4 insulator units per foot of conductor height, the expected outages would be 21 per 100 miles per year. If the conductors are 40 ft. high, the total insulator units per string would be 16. From Fig. 12 this would give a lightning spark-over voltage of 2200 kv. or a gradient to cause spark-over on 55 kv./ft. The expected outages would then be 21 per year per 100 miles of line in country where 100 storms occur per year. If the number of storms per year are 30 rather than 100 the expected outages would be $\frac{30}{100} \times 23 = 6.9$. With a ground wire reducing the voltage to 50 per cent the equivalent insulation is $\frac{0.4}{0.50} = 0.80$. The expected outages with the above insulation and 100 storms per year basis would be 5. While this curve is not yet as complete as would be desired it does give a good indication of what can be expected. Fig. 25 also indicates quite well, from the statistical standpoint, that the outages increase with the height of line, decrease with decreasing insulation, decrease with ground wires, and that a gradient of 100 kv./ft. is the maximum. To indicate this the gradients necessary to cause spark-over are shown on the curve. The outages should become very small when the gradient equals the maximum

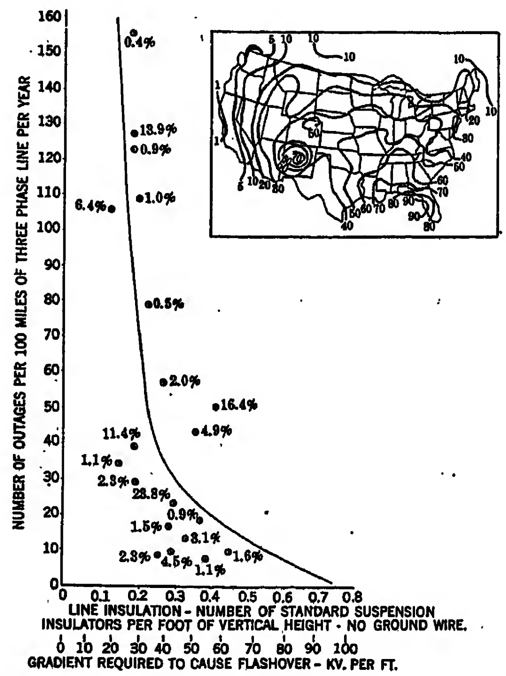


FIG. 25—ESTIMATE OF PROBABLE OUTAGES ON TRANSMISSION LINES FROM A STATISTICAL STUDY

(Reduced to standard basis by dividing insulators by height of conductor, correcting for ground wire effects, and reducing to 100 storms per year. Figures on points indicate percentage of total year-miles used in estimate)

This curve refers to a location having 100 thunderstorm days per year. For other locations take values from curve and apply to section under consideration by multiplying by percentage of 100 thunderstorm days per year as shown on the above map

lightning gradient provided the impulse ratio is about 1.9 as given in Fig. 12. This occurs for a gradient of 100 kv./ft. This value was originally arrived at on a different basis. These data also indicate that the lightning spark-over voltages of Fig. 12 are approximately correct. *Direct stroke outages are indicated when the line insulation is stronger than the maximum calculated induced lightning voltages.*

An example will be given of the use of the data in design of a line. Assume 60 ft. conductor height. At a gradient of 100 kv./ft., the maximum induced voltage, $V = 100 \times 60 = 6000$ kv. With a ground wire arranged to reduce the voltage to 50 per cent, $V = 6000 \times 0.50 = 3000$. Assume 20 insulators are used. From Fig. 12 the spark-over voltage of 20 units is 2700 kv. From Figs. 13 and 14 proper distance from conductor to tower can be obtained. Some outages should be expected because the insulator strength is less than the maximum voltage. By reducing the conductor height greater security could be obtained. It is now interesting to check in an entirely different manner by an entirely different method, the apparent ability of this line to resist lightning. In other words check it by experience gained in practise on similar lines. From Fig. 24 plot a curve for a 60-ft. line with different numbers of insulators and with and without ground wires for 30 storms a year. Plot the same for a 30-ft. line for comparison. It is seen that for the 60-ft. line with ground wire and 20 insulators the number of expected outages would be three or four. With a 30-ft. line and ground wires the maximum voltage would be $V = 30 \times 100 \times 0.50 = 1500$ kv. From Fig. 12 an insulator string of 12 units would have a strength greater than 1500 kv. Referring to the curve, the expected outages for such a line insulated with 12 units would be practically nil.

It is of interest to examine these curves from other angles.

It is seen that the expected outages would be 50 per 100 miles with 14 insulators and a 60-ft. conductor height. With a ground wire reducing the voltage to 50 per cent the expected outages would be 16.

By adding two insulators, a total of 16, the expected outages are 38 without and 12 with the ground wire arranged to reduce voltages to 50 per cent. With two ground wires and a reduction to 40 per cent the expected outages would be about 4. This corresponds to the usual 220-kv. line. With a properly located direct hit wire above the ground wire, and low resistance ground, it now appears feasible to eliminate direct stroke outages. For a 110-kv. line the usual insulation is 7 units. The expected outages would be 130 without a ground wire and 28 with two ground wires. Reducing the height to one-half has a marked effect. While such a curve could not give the exact number of outages for any one line any one year it should give approximate values over several years and be of great help in deciding the economic and technical value of various arrangements.

V. Standard Wave—Coordination

1. Standard Wave. In general fundamental research on different types of gaps, insulators, insulation and different apparatus, such as lightning arresters, and transformers, various special effects must be considered. Careful research must be made with all types of waves. However, it would be of great convenience to have a standard wave particularly for the purpose of making a comparison of various types of insulators, bushings, and gaps. Such data are needed for coordination and to determine the ability to spark over without puncture. Such a wave should be easy to duplicate, should permit of many tests in a short time, and should produce the effects of severe lightning. The most severe lightning effects usually occur with high impulse ratios, particularly where solid insulations are present. This follows because the solid insulation of an insulating member is submitted to higher voltages for steeper impulses and the effect is cumulative. There is no reason to make impulse tests for an impulse ratio approximating unity because the effects are the same as at 60 cycles. A wave giving an impulse ratio of about 1.8 seems reasonable. This could be obtained for example by a uniformly rising wave reaching spark-over in about 2 microseconds or preferably by a standard wave (with 50 per cent sparking) of ½/5 or ½/20. The full fixed standard wave is by far the simplest method and is least subject to error. A greater range of effects could be obtained with a long and a short standard wave. Several impulse ratios could also be obtained by the full standard wave and by fixed wave over-voltage. The fixed full wave method with one or two standard waves is therefore recommended. For testing special types of apparatus it may sometimes be necessary to use a circuit giving proper energy relations of traveling waves on a line.

2. Coordination. Coordination means the adjustment of lightning breakdown voltage between the transformer or other apparatus and the adjacent line insulation so that if lightning voltages become high enough, line spark-over will occur and limit the incoming voltage waves sufficiently to prevent transformer or other apparatus failure. It is not intended to take the place of lightning arresters or other protective devices, but rather to act as a safe-guard against very heavy discharges and in case the arrester is out of service. If the arrester is operating satisfactorily it will prevent spark-over on the coordinated gap. The gap is thus also a good check on the condition of the arrester. Coordination may be effected either by the use of the standard insulation for ½ mile from the station or by a specified gap at the station and within 100 ft. of the apparatus. Coordination permits the use of extra insulation wherever desirable on other parts of the line. Since the coordinated section is relatively short the use of normal insulation on this portion usually has very little effect on the outages. If desirable, extra ground wires can be used over this section. The transformer bushing

is generally made stronger than the line insulation but weaker than the transformer insulation. Coordination has been in use on one 220-kv. line for several years. The coordinating gap has flashed over many times during this period without damage to the transformer.

In setting the coordinating gap or adjusting the line insulation it is important to know if coordination will hold over a wide range of transient wave-shapes. If the setting is made for the standard wave it will usually hold for all impulse conditions. (See Fig. 14 for point gap and insulators.) This follows unless the factor a or β in Equations (1), (2), (3), and (4) varies widely. The necessary margin for any arrangement of gaps or insulation can be readily determined from these equations. In order to make an experimental check, different high-voltage bushings were set up in parallel with insulators and then with a point gap, and tests made for full wave and overvoltages with the ½/5 and 1½/40 waves. Lags varying from less than one microsecond to over 40 microseconds, or impulse ratios for over 2 to 1.2, were thus obtained. The gap and insulator always protected the bushing as determined by spark-over values with the standard ½/5 wave. The values calculated from the equation also checked. An example of this type of test is given for insulators and point-gaps in Fig. 14.

VI. Conclusions

1. The law of breakdown and time lag has been derived from experimental data and is expressed as follows:

$$\beta = \left(1 + \frac{a}{\sqrt{t}}\right) \quad \text{The impulse ratio} \qquad (1)$$

$$t = \left(\frac{a}{\beta - 1}\right)^2 \quad \text{The time lag} \qquad (2)$$

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right) \quad \text{The impulse breakdown voltage} \qquad (3)$$

Where

e_0 = the minimum breakdown voltage—usually the 60-cycle crest value

t = time lag in microseconds

β = impulse ratio

a = factor dependent on the electrode and insulating material

This law, which appears rational, states that a given amount of energy is required to break down insulation and that time and voltage are interdependent. It is quite in agreement with the work in the original paper[1] and applies to breakdown on rectangular waves, on slanting waves of uniformly rising voltage, or to overvoltages on standard waves. By means of the above formula the results for different waves can be calculated and correlated.

2. The three general types of waves, which are rectangular, uniformly rising front, and standard logarithmic, have characteristics and would give results as follows:

(a) A perfectly rectangular wave, because of its shape, would eliminate several variable factors in connection with the analyses of impulse spark-over results. However, due to circuit conditions, it is difficult to produce in practise a wave which more than approximates the rectangular form. With an approximate rectangular wave, practically the same variable factors that other wave forms cause are introduced. Also, this rectangular wave form would be very unlikely to occur in practise from natural lightning sources.

(b) Spark-over on the front of a wave probably is typical of many lightning flashovers in the field. The use of this form of impulse failure is feasible in laboratory studies. However, precise oscillographic records of every spark-over are necessary.

(c) The use of a standard laboratory wave of logarithmic front and tail permits securing impulse breakdown effects close to those associated with most natural lightning surges. By proper adjustment of wavelength and selection of breakdown point on the wave it is also possible to simulate the effect of a rectangular wave, sloping front, or any other wave form. An interesting mathematical relationship showing this equivalent effect can be deduced.

The fixed wave method simplifies the testing problem greatly as it necessitates merely a parallel sphere-gap for measurement purposes and requires no oscillographic records. Overvoltage tests on such waves increase the range. Since it also represents practical conditions, gives the most consistent results and can be made to give the effects of the others in insulator testing, it appears the best standard for comparison. Severe, steep wave-front effects can be obtained with the ½/5 wave, while a large range of results can be obtained with three waves of ½/5, ½/20, and 1½/40.

For testing very special apparatus the slanting front may sometimes be desirable with circuit arrangements to give proper energy relations.

3. Data are tabulated from which the impulse spark-over voltage for a wide condition of waves can be calculated. These data will be added to and corrected for greater accuracy as quickly as laboratory work permits.

4. The field investigation of lightning indicates that:

The average lightning wave, even with maximum voltages sufficient to cause spark-over on a 220-kv. line, can be accounted for by induction, with reasonable assumptions as to size of cloud and rate of discharge.

Spark-overs may be caused by either induced voltages or direct strokes. Direct strokes become of proportionally increasing importance as causes of outages when line insulation is increased.

Voltages giving impulse ratios of the order of 1.8

cause a large percentage of the spark-overs on high-voltage lines.

5. Waves giving low impulse ratios are not representative of average field conditions, and do not give severe enough effects for impulse testing.

6. Statistics compiled from lightning records gathered from widely scattered power systems substantiate the fact that the standard laboratory waves (½/5 and ½/20) discussed above give effects truly representative of average field conditions. These statistics also serve as a valuable basis for considering economically the line insulation necessary under different conditions.

7. It therefore seems quite proper to consider the above standard lightning wave as a rational basis upon which to compare insulator and insulation strengths in the general problem of coordinating line and apparatus insulation.

8. Coordination of system insulation on transmission lines has been used on important systems and its value is now recognized. The law of time lag given above permits the proper coordination under all conditions.

VII. Acknowledgments

The author acknowledges the valuable assistance of Messrs. W. L. Lloyd, Jr., H. L. Rorden, J. C. Dowell, and L. G. Levoy in carrying out the laboratory work, and of Dr. J. T. Lusignan, Jr., and Mr. L. V. Bewley in formulating the data.

Bibliography

1. *The Effect of Transient Voltages on Dielectrics—I*, F. W. Peek, Jr., A. I. E. E. Trans., Vol. 34, 1915, p. 1857.

2. *Lightning*, F. W. Peek, Jr., A. I. E. E. Trans., Vol. 48, 1929, p. 436.

3. *Law of Corona—I*, F. W. Peek, Jr., A. I. E. E. Trans., 1911, p. 1889.

4. "Dielectric Phenomena in High Voltage Engineering," McGraw-Hill Book Company, 1929 Edition.

5. "Lightning and Its Effect on the Design of Transmission Lines and Apparatus from the Economic and Engineering Standpoint," F. W. Peek, Jr., Paper prepared for the World Power Conference, Berlin, Germany, 1930.

"Time Lag of Insulators," Wade and Smith, *Electrical World*, August 18, 1928.

Surge Characteristics of Insulators and Gaps, J. J. Torok, A. I. E. E. Trans., 1930.

Discussion

For discussion of this paper see page 1496.

Rationalization of Transmission Insulation Strength—II

Need for, Present Status, and Necessary Developments for Carrying Through

BY PHILIP SPORN*

Member, A. I. E. E.

Synopsis.—This paper, prepared with the cooperation of the members of the Insulator and Lightning Subcommittee, points out the present need for rationalizing transmission system strength on the basis of lightning voltage. The higher grade of service demanded of transmission systems today requires fewer interruptions. It is pointed out that for a four year period the line interruptions due to lightning on an extensive 132-kv. network average 75 per cent of all line outages.

Apparatus failures due to lightning, while not numerically great, can be materially reduced, if the system insulation is coordinated on the lightning basis.

Over-insulation of lines has been tried in some cases, particularly on wood pole lines, with varying degrees of success in reducing line outages. But this method of attacking the lightning problem does not consider the protection of station equipment where the most costly apparatus is subject to damage, and where apparatus damage may result in long service outage.

It is pointed out that additional knowledge is necessary on lightning strengths of insulation and apparatus to rationalize system voltage strengths on a lightning basis. This information is gradually being secured by various groups working on the problem.

To aid in solving the lightning problem it is proposed a set of standard test waves be adopted by which insulation and apparatus, if possible, may be tested. With this knowledge of the lightning insulation strength of apparatus it will be possible to design transmission systems more intelligently, as far as insulation is concerned, on a lightning basis in addition to the present 60-cycle basis.

On the basis of field data secured last year on wave-shapes of natural lightning, three standard test waves are proposed having voltage time characteristics similar to those actually observed.

Lightning voltage, it is pointed out, should be designated in units peculiar to lightning, and not in terms of 60-cycle voltage values.

* * * * *

I. INTRODUCTION

THIS paper is intended to represent the standpoint of the Insulator and Lightning Subcommittee in regard to rationalization. A standpoint representative of the committee as a whole, in so far as that is possible, is given. This does not mean, however, that in every respect it meets with the unanimous endorsement of every member of the Subcommittee; where divergencies of opinion exist the points of view expressed in the paper are those of the chairman and of a majority of the committee rather than of the committee as a whole. In particular is this true in regard to the question of standardization of a lightning wave. Several of the committee members believe strongly that a lightning test wave cannot be standardized at the present time; another group, however, feels equally convinced that a single or a group of waves can be standardized at the present time to great advantage and to the great benefit of all those interested in the advancement of the electrical insulation art, particularly as it affects the transmission system. The chairman of the subcommittee is among those favoring the adoption of a series of standard lightning test waves and the views with regard to this subject, expressed in this paper, can be taken as representative of his views and the majority of the subcommittee.

II. THE NEED FOR RATIONALIZATION

The general subject of rationalization of transmission system insulation strength, although perhaps known and practised for some time previous, was presented formally before the Institute in the Spring of 1928.[1] Subsequent events have demonstrated the importance of this phase of engineering and the need for its further development. A review of this development ought to be of help in obtaining a full idea of the significance of the problem.

In the paper already referred to,[1] it was pointed out that the principal high voltages which have to be insulated for are those due to lightning; in other words, the unsolved lightning problem is the one barrier to continuity of service. Further data, accumulated since then, have resulted in a further check of the correctness of this statement. For example, on the 132-kv. system of the subsidiaries of the American Gas and Electric Company the lightning outages in per cent of total outages have been as follows:

In 1926—81.6%
In 1927—77.2%
In 1928—68.2%
In 1929—75.7%

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Chairman Insulator and Lightning Subcommittee

Members: Philip Sporn, J. G. Hemstreet, W. W. Lewis, C. A. Jordan, J. H. Cox, Herman Halperin, I. W. Gross

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

1. For references see Bibliography.

Data of the above type can leave no question of the predominance of lightning as the source of trouble; and a conclusion is reached that the insulation for lightning is the one factor that has to be particularly watched out for; in other words, that the lightning problem is the paramount insulation problem. Nor is there any doubt that at the present time lightning is only very little controlled. Yet in the face of all that, the power frequency (which in most cases means 60 cycles) is the frequency at which insulation strength is measured and in terms of which it is designed, built, sold, and installed. The logic of this is rather hard to defend; in fact one may doubt, and this has been expressed previously, that there is any logic in it.

The unhappy results of lack of rationalization continue to pile up. In a previous paper[1] there was cited a considerable number of failures on 132-kv. transformers; others have since developed. For example, there was a case on an extensive 132-kv. system on the property of one of the subsidiaries of the American Gas and Electric Company where a 10,000-kv-a. transformer that had been in service less than a year failed during a lightning storm at a substation where this transformer was tapped to the line. A surge recorder connected on each of the three phases of the circuit near the transformer showed a maximum crest voltage of 1050 kv. on two phases and 600 kv. on the third phase. The failure produced a short circuit between the transformer turns and coil sections at some distance from the line coils; the bushing in this case was entirely unharmed. A lightning arrester installed on the same bus and on which surge recorders were again connected showed current in the three phases of 96, 262, and 310 amperes respectively.

In another instance, during a lightning storm high voltage entered one phase of a 132-kv. transformer bank and jumped through the oil to the ground sleeve of the bushing. The transformer was put back into service and was apparently entirely satisfactory, but at the end of four hours tripped again. Subsequent examination showed that an arc had gone from the end to the middle of the winding by two paths, one through oil and barrier bolts to the tap changer and the other across the top of the coils. Two 132-kv. lightning arresters were connected to the incoming lines throughout this entire period; the arrester ground resistances were found to be five ohms in one case and one ohm in the second.

Again, a number of cases has since been experienced with failure of 132-kv. coupling capacitors, used for carrier current communication, these capacitors being in each case of the dry mica type. In each case the failure was during a lightning surge on the system. The electrostatic capacity of these capacitor groups was 0.001 microfarad. It is obvious that in the cases of these coupling condensers the electrostatic capacity of 0.001 microfarad which is an appreciable value, was not sufficiently high to act as a lowering medium for the surge, to render the capacitor self-protecting. Experience with failure of other important apparatus of the same nature is available; it cannot, of course, all be cited here.

There is another aspect of the generation and transmission problem which makes insulation rationalization very necessary and that is the development of high-voltage generation. With the higher generating voltages obtainable today the ideal always sought, but not often found, of distribution at generating voltages is again obtainable in many cases; but here again, the problem of insulation for high voltages, where feeders connected to overhead transmission systems are to be fed from these busses, is complicated by the problem of lightning strength of the generator windings.

Heretofore only a mild form of the problem had to be met. It is obvious that to take full advantage of the important advance in generator voltages the knowledge obtained on lightning insulation strength must be applied to the knowledge that has yielded the higher generator voltage. The introduction of a 1 to 1 transformer, for example, is not solving the problem; it is very definitely slurring it and running away from it.

The development of the idea of overinsulation of transmission lines is of rather recent occurrence and once again contributes to the chaos instead of solving the problem of rationalization of insulation. In the last few years there has been a very definite economic drive to obtain transmission line service with fewer outages. The types of load that have been taken on have in most cases demanded service continuity of the highest sort, and this has led to the raising of the insulation level to heights undreamed of a few years ago. Thus, we have had a recent 220 kv. development designed with eighteen 5¾ in. units for the transmission line. Again, the use of wood poles, wooden crossarms, and braces[2, 3] has spread over the last few years with the probability that their use will spread further in time to come. In many of these cases the use of wood has resulted in the setting up of insulation barriers that have permitted voltages of as high as 2,450,000 volts to be measured on moderate voltage transmission lines, with an indicated voltage in the order of 4,000,000 volts at the point of flashover.

Still another problem that adds to the gravity of the insulation situation has been the uncertainty of lightning arrester operation. The case of the 10,000-kv-a. transformer, where an arrester was installed very close to the transformer, which failed from a lightning impulse, has been cited. The transformers referred to in the earlier paper,[1] had in some cases lightning arresters installed, in other cases none, with apparently very little difference in behavior. In the case of the 132-kv. transformer where an internal bushing flashover occurred lightning arresters were installed near the transformer terminals. In another case where arrester performance was being measured voltages on the three phases of the arrester of 1300, 900, and 1000 kv. were

measured by the klydonograph and amperages of 500 and 650 measured on the phases corresponding to the first two voltages. Here it will be noticed that, within the limits of accuracy of the instrument employed, it was shown an arrester permitted the piling up of a voltage of 1300 kv. although it was discharging a considerable current. It is true of course that within the last year there have been developed new types of arresters,[4, 5] but after all, these arresters still have to prove themselves. It must not be forgotten that the electrolytic arrester, when it was developed, was confidently believed to be the ultimate in lightning protection.

In short, it may be said that while service on transmission systems has been in general pretty good it has been only that; on the other hand the crying need is for good and practically perfect service. There are still too many cases of trouble that interfere with this very necessary and ideal standard, and much blame for such trouble can undoubtedly be ascribed to the failure to properly rationalize system insulation strengths. The system not being designed or insulated to withstand the dangerous disruptive forces of lightning voltages, it is the fault of the *system* designer alone if these forces ultimately cause a failure in a portion of the system and raise all the havoc with service concomitant with such a failure.

III. The Present Status of Rationalization

A first examination of the present status of rationalization gives the impression of a rather hopeless situation. Very little progress has been made since 1928. To date, therefore, the same chaotic situation with regard to data on insulation strength, particularly with regard to data on competitive equipment, exists as was pointed out previously. In fact, the more the situation is examined the more confusing it appears. Even the 60-cycle flashover value for standard suspension units *of the same spacing and of substantially the same design* as given by various manufacturers does not agree; differences of from 10 to 15 per cent are quite common.

As regards the lightning phase there is still apparent the same tendency to let well enough alone. The same idea that service is pretty good and that the situation need not be disturbed is found among many people who ought to take the situation more seriously, particularly when it is taken into account that such an attitude of mind invariably leads sooner or later to a disturbance of cyclonic character. There is still going on a haphazard adjustment or readjustment of insulation values. Points that are found apparently weak are strengthened without too much regard to the rest of the system. As an example of that, the use of wood to further increase the lightning flashover of the transmission line circuit can be cited.

The insulator and bushing manufacturers, it may be stated very definitely, have done little toward the problem of coordination in which they should be vitally interested. The entire problem has apparently been left to the transformer manufacturers (among these only a selected group has obviously been able to tackle the problem intelligently) and to large users of equipment.

And yet, if the situation is examined more closely, it does not appear quite so hopeless. For one thing, the importance of the transmission problem is greater than ever. Larger systems have been developed, and are continuing to be developed, and larger blocks of power are being transmitted and handled all the time. The effect of flashovers, therefore, in these larger systems is not only greater than ever but is also felt in many other directions. Not only is the destructive effect of an arc following a flashover greater with increased power of a system, but, as systems extending over hundreds of miles are put together, new disturbances arise as a result of flashovers. For example, the stability problem is one that has come to the forefront in the last few years.

Again there has been aroused a definite engineering interest in the problem and in its solution. Many organizations who would not have considered it except in the light of a very theoretical sort of study are now at work on the problem. In fact it is not rare at all, at the present time, to find designers of stations and substations who carefully go into the various phases of the problem and pay it as much attention as they formerly gave problems of line and station capacity, switching arrangement, etc. All this stirring of interest and concentration of many various engineering minds on the problem is bound to have a beneficial effect in the direction of bringing a satisfactory solution to the problem.

In the field of accomplishment, while positive and definite results are not obvious, there has nevertheless been achieved a considerable amount of progress. Manufacturers of apparatus, particularly of transformers, and among these again particularly the two largest manufacturers, have been studying the problem of lightning insulation and the problem of coordination and of rationalizing the entire insulation structure. There have actually been developed designs of transformers within the last two years and such transformers have been sold on a so-called self-protecting basis. This, of course, is rationalization, although only partial rationalization. It is highly desirable, and is significant of the progress that has been made; but the field to which it has been applied is altogether too narrow.

In the laboratory many fundamental researches have been undertaken as to the characteristics of various types of insulation under surge conditions. The work of Peek[6] and Torok[7] on the characteristics of insulation as affected by time and voltage is typical of this work. In the field a large number of investigations with artificial and with natural lightning has been carried through and particularly valuable data were obtained during the past year.[8]

Several committees of the Institute have taken the problem for their own and have done a considerable amount of work on it. Among these are the Trans-

former Subcommittee of the Electric Machinery Committee, the Insulator and Lightning Subcommittee of the Transmission Committee, and the Lightning Arrester Subcommittee of the Protective Devices Committee. Each of these has attempted in its way to contribute to the problem of rationalization of the transmission system insulation and each has made some progress, although none of the three has concluded its work. The fact, however, that the problem is being attacked from these three angles is significant and offers the hope that the solution, when it is finally reached, will be a broad one and will not be one satisfactory from one phase or from one angle of the situation only. In this connection, it may be very illuminating to describe the experience covering one important phase of the problem which was attacked by one committee and which, through the intervention of the activities of another committee, resulted in perhaps a different action being taken than would otherwise have occurred and in bringing about a situation more in conformity with the broad point of view necessary to maintain in problems of this type.

This situation involved a proposed addition to the Standards of the A. I. E. E. for transformers, induction regulators, and reactors. The Transformer Subcommittee of the Electric Machinery Committee had been considering the question of impulse strength of transformers. As a result of these discussions the subcommittee came to the conclusion that it would be desirable to recommend an addition to Section No. 13 of the Standards (dealing with transformers, induction regulators, and reactors) to embody recommendations on the relationship between transformer and line insulation strength. This relationship was to be given in the form of an appendix to the Standards, the principal paragraph of which is given below:

RECOMMENDATIONS ON RELATION OF TRANSFORMER INSULATION TO ADJACENT LINE INSULATION

(a) Transformers Receiving Standard Dielectric Tests—Para. 13-400 and 13-401.

Apparatus conforming with the standards of dielectric test should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to ground of non-shielded suspension type insulators having a 60-cycle r. m. s. dry flashover in accordance with Table I.*

TABLE I

Rated circuit voltage	Transformer 60-cycle test voltage	Insulator 60-cycle dry flashover voltage
Kv.	Kv. r. m. s.	Kv. r. m. s.
69	139	250
92	185	350
115	231	400
138	277	450
161	323	550
196	393	640
230	461	725

*Commercial methods for determining the impulse strength of transformer windings by acceptance test in the factory are not feasible. However, investigations in the laboratory show that the impulse strengths of transformer insulation and of standard line insulators or of air-gaps vary similarly with different forms of waves, also that the impulse ratio of strings of line insulators of different lengths is approximately constant for the same impulse wave. The forms of impulse waves actually occurring on transmission lines have not been fully determined. For these reasons, the impulse strength of transformer windings are expressed in terms of the 60-cycle dry flashover voltage of either line insulator or air-gaps.

The appendix included a long footnote defining the various methods of limiting lightning voltages on the portion of the circuit adjacent to the apparatus to the lightning flashover voltages of line insulators having the 60-cycle flashover voltages given in Table I.

This subcommittee was about ready to make its recommendations to the Machinery Committee when the Insulator and Lightning Subcommittee became interested in the problem and suggested that a matter of this type was of such vital interest to the transmission field, and of so great importance, that it would be desirable that the matter proposed be held in abeyance until such time as the problem could be gone into jointly between the two subcommittees.

After fully going into the situation, the Lightning Subcommittee decided that it would not be to the best interest of all concerned to have the proposed standard adopted, and it registered its opposition accordingly. In the course of a joint meeting between the two committees, where this entire question was threshed out, the Lightning Subcommittee pointed out the following specific objections to the proposed standard.

1. The material bearing on this subject is in a state of flux and should therefore not be put in standard form, under these conditions.

2. There is a strong feeling among engineers that operating practise should not be coordinated as a part of A. I. E. E. Standards.

3. While the proposed Standards do not propose to prescribe standard practise, it would in fact result in doing that. The data being obtained at the present time may quite likely result in standard practise changing considerably in the future.

4. Impulse strength should be expressed in appropriate units and not in secondary units, such as 60-cycle voltage. With the advance made in lightning research it ought to be possible to do that within the next two or three years.

5. The matter of coordination or rationalization of impulse strength of transformers and line insulation should not reach a stage of even tentative standards, but should be handled by papers presented before the Institute by interested parties having knowledge of the matter.

A subsequent canvass and discussion of this situation with the rest of the Transmission Committee resulted in a complete approval by its membership of the stand taken by the Lightning Committee. As a result, the proposed standard was not approved; the matter is instead being presented in the form of a symposium before the Institute, this paper being one of that group.

IV. Necessary Developments for Carrying Through the Problem of Rationalization

The foregoing data have been presented with a view of showing the still chaotic condition of the present insulation situation and the various influences that are at work to bring some order out of the chaos. They show that

while the situation is still in a considerable state of fog and confusion, it is not entirely hopeless. The question arises as to what can be done to carry rationalization completely through.

A large number of items is needed. The most important of these are, however, the following:

1. *Knowledge as to Lightning Strength.* If, as is admitted, the major insulation problem is that under lightning conditions, then it is almost axiomatic that, before any definite progress can be made in design or coordination, the first thing necessary is the knowledge as to fundamental lightning strength of all links of insulation in the transmission chain. Expressing this strength in terms of any other unit, for example, in terms of the power frequency unit, is most certainly not satisfactory and will only result in delaying progress in the solution of the problem. It is not conceivable that for all classes of insulation the relationship between 60 cycles and lightning strength can remain the same for varying lightning voltages encountered. Nor will the lightning problem be placed on a stable and scientific foundation so long as a unit representative of insulation strength of a piece of apparatus under lightning conditions is shied at. The form which this lightning strength is to take is immaterial so long as the unit is one definitely expressive of lightning conditions. Whether this is to take shape in the form of volts and time or volts in terms of a standardized impulse wave is immaterial so long as a break is definitely made, and it is expressed in terms of its own rather than in 60-cycle or power frequency values.

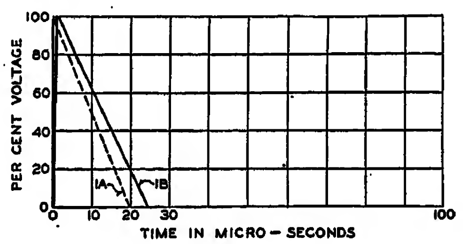

FIG. 1—PROPOSED STANDARD IMPULSE TEST WAVE

2. *Necessity for Standard Lightning Wave.* While, as pointed out above, the necessity of expressing lightning insulation strength in terms of a unit of its own is of prime importance and the form in which this is to be expressed is secondary, there is no question but that the establishing of a standard lightning wave will considerably accelerate the solution of the problem. Under present conditions data gathered by various investigators are not readily comparable. Some investigators have even cautioned that their data are not comparable with results obtained by others. The adoption of a standard test wave would automatically remove all these difficulties. The standard could be changed from year to year or as required until definite information is made available as to what could serve as a permanent standard.

It is admitted that a single wave would cover the situation rather unsatisfactorily; but it is not necessary to limit the standard to a single wave. It is possible, for example, to adopt three different waves and this is the proposal now made in this paper: That three waves referred to as 10-microsecond, 30-microsecond, and 90-microsecond waves* be adopted. That such an

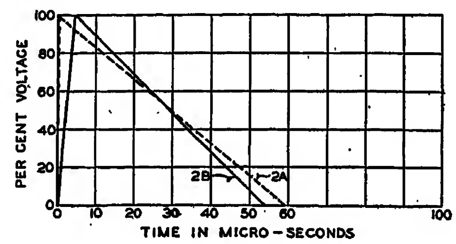

FIG. 2—PROPOSED STANDARD IMPULSE TEST WAVE

arrangement would represent a situation in fairly close conformity with the data as gathered to date can be seen from Figs. 1, 2, and 3. In each of the above three figures curve *A* represents one of the three proposed standards, Fig. 1, Curve 1-*A* showing the 10-microsecond standard, Fig. 2, Curve 2-*A*, the 30-microsecond standard, and Fig. 3, Curve 3-*A*, the 90-microsecond standard.

The *B* curves in Figs. 1, 2, and 3 are based on 15 natural lightning voltage waves obtained in the field during the 1929 lightning season.[9] The crest value of 12 of these waves varies from 500 kv. to 1260 kv. The voltage time characteristics of these 15 waves are as follows:

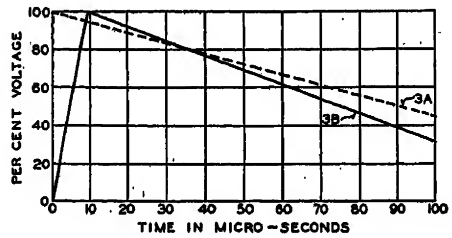

FIG. 3—PROPOSED STANDARD IMPULSE TEST WAVE

TABLE II

(TIME IN MICROSECONDS)

	To Crest	Drop to 50% Crest
Maximum	11	69+
Minimum	2.5	16.
Average	6.3	30.2

The *B* curves, based on Table II have the following characteristics:

*It is proposed that all waves have a ¼-microsecond front; the time referred to in the designation of the waves may be considered as a special time constant and is the value in microseconds required for the wave to fall to 50 per cent of its crest value.

TABLE III
(TIME IN MICROSECONDS)

	Curve	To Crest	Drop to 50% Crest
Maximum..............	3-B	10	75
Minimum..............	1-B	1*	15
Average................	2-B	5	30

*This value has been taken as less than one-half the observed value to allow for possible errors in determining wave fronts in the field, and further, to recognize the limitations of field observations where it is believed in many cases the lightning stroke did not occur close to the line.

It will be noted that in each case the proposed standard is a very fair approximation of the range in lightning wave-shape that it is intended to cover and it is believed that in the light of existing data, therefore, the three proposed standards, or slight modifications of them, can very definitely be undertaken. It is recognized that the adoption of standards as above would fall considerably short of the ideal standard, but the benefits to be obtained through the adoption of this temporary standard are so great as to decidedly make worth while its immediate adoption.

3. *Data as to Variation of Lightning Strength of Insulation.* The lightning strength of insulation and of the apparatus is dependent upon the type of wave that the apparatus is subject to, or put in another way, it is dependent not only upon voltage but upon the time of application. The specific data as to characteristics of all apparatus under these conditions are desirable. Here, however, it should be recognized that while specific data covering the volt time characteristics of apparatus can and will ultimately be obtained for all classes of material, the process is necessarily long and tedious.

It is admitted that data on apparatus insulation strength expressed in terms of a particular impulse wave, or in terms of a group of waves, will give, to say the least, a good approximation of the complete data referred to above, and would certainly give data more suitable than any available at the present time. Further, such data could be obtained rather quickly. It is necessary, however, if the gathering of such data is to be undertaken, to have a standard wave or a series of waves, such as the three outlined above definitely adopted.

4. *The Determination of Relative Frequency and Importance of the Direct and Induced Strokes.* There is at the present time a very divergent opinion as to relative frequency and importance of direct and induced strokes in high-tension circuits. Experimental data and opinion are about equally divided in assigning of paramount importance to the direct stroke or the induced stroke as a source of trouble. Such divergence does not exist with respect to low-tension lines, where it is admitted that the direct and induced strokes are perhaps equally important as a cause of trouble. But the diverse opinion with regard to high-tension circuits makes it imperative, more than ever, to obtain sufficient information to clarify the situation and find out the true state of affairs. It is obvious that the method of protection adopted may vary considerably and will depend to a great extent upon which type of disturbance protection is being provided for. This makes the necessity of authoritative data on that particular phase extremely important.

5. *Further Data on Shape of Natural Lightning Waves.* While a considerable amount of field data was obtained during the last year on the shape of natural lightning waves, these data are far from complete and far from being conclusive. Too many were obtained on waves at a considerable distance from the point of origin. While mathematical analysis can give a solution for the probable shape of the original lightning wave, if the distance from the point of disturbance is known, such data are of course difficult to obtain. A more satisfactory solution will be to obtain records of direct strokes. Such data when obtained can be immediately utilized in a revision of any standard for lightning waves that may be in existence at that time.

6. *More Extensive and Accurate Field Data on Performance of Lines and Apparatus.* It has been pointed out in this paper that a great deal of progress has been made over the past two years in the accumulation of laboratory data with artificial lightning and in collecting data in the field laboratories with natural lightning and also with artificial lightning. A third phase of investigation, which has also advanced considerably, has not been mentioned, but its importance is equal to each of the other two classes of investigations. That is the detailed record and analysis of actual operating experience with lines and apparatus under various conditions of lightning. The natural operating tendency to bury the dead has to be fought in this case, and each operating fault or trouble should be made to yield its share of knowledge to the solution of the problem. The keeping of case histories of this type is most certainly an important contribution to the solution of a problem as important as this. Considerable progress has been made, particularly in the last few years, in the keeping of such data and in its publication but there are still too many cases where a process of reasoning is indulged in to justify the withholding of such information. Nothing, of course, is accomplished by that except the postponement of the day when the complete solution of the problem will have been obtained. Particular emphasis ought to be laid on the recording and analysis of data relative to the lightning conditions and if possible to the data regarding intensity of the lightning storms encountered.

7. *Fundamental Data as to the Effects of Various Types of Station Designs and Apparatus on Incoming Lightning Waves.* While some data have been obtained on this phase of the problem, much more information of an authoritative nature is needed to determine definitely the effect on incoming waves of various types of structures, and terminal apparatus; also the effect of travel of an incoming wave through such apparatus, on the apparatus itself, and upon the con-

nected equipment. In particular is it necessary to have further data on the effect of bushings, cable terminals, insulated cable, and similar apparatus.

8. The Segregation of Insulation Strength, Particularly Lightning Insulation Strength, from Operating or Nominal Voltage Rating. It has been brought out again and again that insulation strength under lightning conditions differs for different materials that may have the same strength under power frequency or 60-cycle conditions, and yet it may be desirable that all these pieces of apparatus have the same or definitely related values of lightning strength. The logical procedure for obtaining this is to specify insulation strength and operating voltage independently. By doing this the ideal aimed at, namely of obtaining for each system the insulation strength needed for that particular system, would most certainly be advanced. This of course has already been previously proposed.[1]

9. Authentic Data on 60-Cycle Flashover Values. In many respects the situation with regard to 60-cycle data is indicative of the entire situation. While 60-cycle flashover data are not of paramount importance in the rationalization problem, it is a fact that operating voltages and the insulation characteristics at operating voltages cannot be entirely neglected. It certainly is not possible to entertain much hope of putting any order into the situation with regard to so complex a problem as lightning insulation if the problem of insulation value at 60-cycle values is in as confused a state as it is at the present time. It would seem that as a prelude to the rationalization of the entire problem of insulation, first, and without delay, a definite standard, sufficiently detailed and specific, be adopted for measuring 60-cycle values, so that measurements taken at any reliable laboratory will agree within the limits of accuracy of the measuring apparatus used with measurements taken at any other laboratory. This is far from the condition today.

V. Conclusions

1. The higher standards of service reliability required of the electrical art, the increase in size of the generating stations, and therefore the growth in the amounts of power handled over transmission systems, have placed heavy and increasing responsibility on the design and performance of the high-tension transmission systems. Lightning being the cause of approximately 75 per cent of service interruptions on high-voltage transmission systems, it is the most important factor which must be brought under full control, in order to bring the service of these systems within the necessary requirements of the electrical art today.

2. There is evident at the present time, as in the past, a continuation of a practise of insulating one portion of a transmission system without too much regard to the rest of the system. Too often when service failures occur, the weak points are more highly insulated, with the transfer of trouble to another portion of the system.

3. The conditions outlined under 1 and 2 above show very forcefully the need of rationalizing system insulation strength on the basis of performance under lightning conditions.

4. Some steps in this direction have been made and numerous developments are under way which show that the gravity and importance of the problem are fully realized. Several committees of the Institute are working on the problem, and many fundamental researches are under way in the laboratories and in the field. Very little that is definite has as yet been accomplished.

5. It has been shown that a continuation of many of the fundamental lightning researches are now being carried out in the field and in the laboratory are highly essential to the carrying through of the problem of rationalization.

6. It has also been shown that one of the great obstacles to such a rationalization program is the failure to adopt some definite unit in which to express lightning insulation strength. To express it in terms of 60-cycle strength, when what is aimed at is rationalization on the basis of lightning insulation strength, seems illogical for several reasons:

(a) It is not known that the relationship between 60-cycle and lightning voltage is the same for all types of insulation generally used, even for one given type of lightning wave.

(b) The ratio of 60-cycle to lightning voltage breakdown of apparatus differs with the variations in design of a piece of apparatus even for a fixed lightning wave.

(c) There is at the present time a lack of agreement on the 60-cycle dry flashover values on insulators of equivalent design as determined by data obtained at different laboratories of recognized standing. It would therefore appear to be better and more desirable to standardize lightning insulation strength on the basis of a lightning wave of definite characteristics of its own rather than on a 60-cycle basis.

7. As a first step in this plan, a set of three standard impulse waves is proposed in terms of which all types of insulation are to be tested. All three waves considered are to have a ¼-microsecond front and are to attenuate to 50 per cent of crest value in 10, 30, and 90 microseconds respectively. The values and shapes chosen are very similar to, and are based on, wave-shapes of natural lightning obtained on actual transmission lines, and ought therefore to approximate actual conditions insulation and apparatus may have to withstand in the field. These shapes may have to be altered from time to time when, and as, additional field data show it to be necessary. It is recognized further that it may not be commercially feasible to apply these waves at the

present time to some types of apparatus with built-up insulation. It is believed, however, that the adoption of these test waves will hasten the time when such apparatus can be so tested; certainly it will make possible the determination of the lightning strength of various designs and accelerate the general problem of research of lightning strength of various types of apparatus, since it will make possible the comparison and checking of data obtained in different laboratories and by different observers.

8. It is recognized that electrical breakdown of insulation is a function of both voltage and time, and that this type of data should be obtained for all types of insulation and should ultimately be obtained for all types of apparatus. It is believed, however, that the obtaining of such data will take a great deal of time; but the problem cannot wait. The proposed system of standard waves will, however, make possible the obtaining of much data and these data are fundamental and necessary if an advance in rationalization is to be made.

9. The lightning strength and operating voltage of transmission systems are independent, as previously pointed out, and as once more emphasized here. The lightning strength will depend to a large extent upon the type of service which a system is called upon to deliver, and not upon its operating voltage. It is believed that a distinct advantage will result in rationalizing insulation of transmission systems by considering the lightning strength independent of the normal frequency operating voltage.

Special acknowledgment is due Mr. I. W. Gross, Secretary of the Lightning Committee, for the help given by him in the preparation of this paper.

Bibliography

1. *Rationalization of Transmission System Insulation Strength*, by Philip Sporn, A. I. E. E. TRANS., Oct. 1928, p. 998.

2. *Impulse Insulation Characteristics of Wood Pole Lines*, by H. L. Melvin, A. I. E. E. Quarterly TRANS., Vol. 49, Jan. 1930, p. 21.

3. *Transmission Research and Design with the Field as a Laboratory*, by F. E. Andrews and C. L. Stroup, A. I. E. E. Springfield Meeting May 7-10, 1930.

4. *Development of the New Auto-Valve Arrester*, by J. Slepian, R. Tanberg, and C. E. Krause, A. I. E. E. Quarterly TRANS., Vol. 49, April 1930, p. 404.

5. *Thyrite, a New Material for Lightning Arresters*, by K. B. McEachron, A. I. E. E. Quarterly TRANS., Vol. 49, April 1930, p. 410.

6. *Lightning—Progress in Lightning Research in the Field and in the Laboratory*, by F. W. Peek, A. I. E. E. TRANS., April 1929, p. 436.

7. *Surge Characteristics of Insulators and Gaps*, by J. J. Torok, A. I. E. E. Quarterly TRANS., Vol. 49, July 1930.

8. *Lightning Symposium*

By: J. H. Cox & Edward Beck
J. J. Torok
R. N. Conwell & C. L. Fortescue
R. H. George & J. R. Eaton
K. B. McEachron, W. J. Rudge, J. G. Hemstreet
N. N. Smeloff & A. L. Price
Philip Sporn & W. L. Lloyd, Jr.
W. W. Lewis & C. M. Foust, A. I. E. E. Quarterly TRANS., Vol. 49, July 1930.

9. *Lightning Investigation on 220-Kv. System of Pennsylvania Power and Light Co.*, by Smeloff & Price; *Lightning on Transmission Lines*, by Cox & Beck, A. I. E. E. Quarterly TRANS., Vol. 49, July 1930.

Discussion

For discussion of this paper see page 1496.

Recommendations on Balancing Transformer and Line Insulations On Basis of Impulse Voltage Strength*

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Fellow, A. I. E. E. Fellow, A. I. E. E.

Synopsis.—The danger of over-insulating transmission lines without a corresponding increase in the insulation of connected apparatus is pointed out.

To avoid trouble from lightning reaching the apparatus, the Transformer Subcommittee of the Electrical Machinery Committee has prepared a set of proposed rules covering: (1) A practical method of defining the impulse strength of transformers, and (2) recommendation on coordinating the transformer and adjacent line insulation on the basis of impulse voltage strength.

It is pointed out that commercial methods for determining the impulse strength of transformer windings by acceptance test in the factory are not feasible. However, investigations in the laboratory show that the impulse strengths of transformer insulation and of standard line insulators or of air-gaps vary similarly with different forms of waves; also that the impulse ratio of strings of line insulators of different lengths is approximately constant for the same impulse waves. The forms of impulse waves actually occurring on transmission lines have not been fully determined. For these reasons the impulse strength of transformers is expressed in terms of the 60-cycle dry flashover voltage of non-shielded suspension type insulators.

If the transformer and line insulation are properly balanced with a given wave, it eliminates the necessity of having to consider the different shapes of waves encountered in practise.

Three methods are recommended for coordinating the transformer and line insulation, namely, (1) the use of an effective lightning arrester; (2) the use of a horn-gap; and (3) the maintenance of average line insulation for a limited distance from the station.

* * * * *

General

FOR a great many years it has been the prevailing practise in the United States to correlate the amount of insulation used in a transformer and the value of the dielectric test which it receives with the voltage of the circuit on which the transformer operates. So long as the level of line insulation was kept at a reasonable value, this method worked out very satisfactorily.

Lightning has been the chief source of the abnormal transient voltages which on account of interruptions to service caused by line flashovers give serious concern to operating engineers. As a result, in an effort to remedy this condition, transmission engineers have been adding more and more insulation to their lines. The need for a more rational basis for insulating high-voltage transmission systems was pointed out by Philip Sporn in 1928.[1]

Where lightning is not severe, increasing the line insulation for normal service conditions has not resulted unsatisfactorily, but it is obvious that if the practise is continued without regard to the insulation of apparatus, trouble will result, as it has in some cases, because the maximum lightning voltage reaching the apparatus is limited only by the height and insulation of the adjacent lines and by protective devices, and is in no way related to the circuit voltage except in so far as the insulation of the circuit may change with the voltage.

The need of new insulation standards on account of this practise of increasing the line insulation has long been recognized by interested manufacturers and operators, and may now be said to be a necessity. Failure to adopt such standards has been due chiefly to lack of general recognition and acceptance of their proper governing factors, together with the difficulties of verifying them in the completed apparatus. Commercial methods for demonstrating the impulse strengths of transformers by acceptance tests in the factory are still not feasible. To make such a test on a transformer might cause undetected injury which would later result in failure in service; on the other hand, sufficient field experience and experimental data are now available by which it is possible to set up certain standards for the coordination of line and apparatus insulation.

Research and experimental investigations carried on by both manufacturers and operators within the past few years have yielded a great deal of new information relating to the impulse voltage strength of transformers, the impulse voltage arc-over of line insulators as determined by the laboratory, and to the magnitude and character of lightning voltages occurring on transmission lines as determined in the field.

Realizing the need of a more rational method of insulating high-voltage transformers the Transformer Subcommittee of the Electrical Machinery Committee in 1927 undertook the preparation of a set of recommendations for defining the impulse-voltage strength of transformers and for balancing the transformer with the adjacent line insulation.

While these recommendations have been completed

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1. For numbered references see Bibliography.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

and are used by the manufacturers for expressing the impulse strength of transformers, they have not yet been recognized by the Institute for coordination purposes.

Before attempting to get any action by the Institute, it was agreed that the Transformer Subcommittee and the Lightning Subcommittee of the Transmission Committee sponsor the symposium of papers being presented at this session. It is hoped that as a result of all these papers, a definite set of rules can be agreed upon which will be acceptable to all concerned.

The purpose of this paper is to give the recommendations prepared by the Transformer Subcommittee together with a discussion of some of the more important phases of the subject matter.

Proposed Rules

The proposal is divided into two distinct parts—Part I dealing with a method of defining the impulse strength of transformers, and Part II giving recommendations on coordinating the transformer and adjacent line insulation.

PART I

Impulse Voltage Strength of Transformer Insulation

(a)—*Transformers Receiving Standard Dielectric Tests, as Specified in Par. 13-400, A. I. E. E. Standards No. 13.*

Apparatus conforming with the standards of dielectric test should be so designed that their impulse strength against lightning is greater than the impulse flashover voltage to earth of non-shielded suspension type insulators having a 60-cycle r. m. s. dry flashover in accordance with Table I.*

TABLE I

Rated circuit voltage	Transformer 60-cycle test voltage	Insulator 60-cycle dry flashover voltage	Corresponding† No. of insulator disks spaced 5¾ in. apart
Kv.	Kv. r. m. s.	Kv. r. m. s.	
69	139	250	4
92	185	350	6
115	231	400	7
138	277	450	8
161	323	550	10
196	393	640	12
230	461	725	14
	510†	810†	16
	570†	895†	18
	625†	980†	20

(b)—*Transformers Receiving Higher Than Standard Test.*

If the 60-cycle dry flashover of the adjacent line insulation is greater than the value given in Table I, and is not locally limited to that value, transformers having a dielectric test corresponding to the actual adjacent line insulation should be used.

(c)—*Transformers Receiving Lower Than Standard Test, as Specified in Par. 13-402 (n), A. I. E. E. Standards No. 13.*

Transformers used with solidly earthed neutral and having the reduced insulation test of 2.73 times line to neutral voltage should have an impulse strength equal to that of a standard transformer for the next lower circuit voltage.

*Commercial methods for determining the impulse strength of transformer windings by acceptance test in the factory are not feasible. However, investigations in the laboratory show that the impulse strengths of transformer insulation and of standard line insulators or of air-gaps vary similarly with different forms of waves; also that the impulse ratio of strings of line insulators of different lengths is approximately constant for the same impulse waves. The forms of impulse waves actually occurring on transmission lines have not been fully determined. For these reasons, the impulse strength of transformer windings is expressed in terms of the 60-cycle dry flashover voltage of line insulators.

†These do not appear in the rules as proposed, but are given here merely for reference purposes.

PART II

Recommendations for Coordinating Transformer Insulation with Line Insulation in the Field

Limitation of lightning voltages, on the portion of the circuit adjacent to the apparatus, to the lightning flashover voltages of line insulation having the 60-cycle flashover voltages given in Table I may be accomplished by the use of one or more of the following methods:

Method No. 1.—An effective and properly applied lightning arrester connected to the circuit within 100 circuit feet (30 meters) of the terminals of the apparatus.

Method No. 1 furnishes the most effective protection, but in the absence of Standards for Lightning Arresters and their installation, Method Nos. 2 or 3 should always be used in combination with Method No. 1. If the impulse strength of the supporting insulation of the arrester conforms to the impulse strength of the gap with settings as given in Table II, then no additional parallel gap is necessary.

Method No. 2.—A suitable safety gap connected between each conductor of the circuit and earth within 100 circuit feet (30 meters) of the terminals of the apparatus with gap setting not in excess of the flashover voltage given in Table II.

TABLE II

Rated circuit voltage	Transformer—60-cycle test voltage	Gap—60-cycle dry flashover voltage
Kv. r. m. s.	Kv. r. m. s.	Kv. r. m. s.
69	139	185
92	185	240
115	231	300
138	277	355
161	323	410
196	393	500
230	461	585

These values apply to either arcing horns or rings attached to insulator strings or to points mounted separately. If rings are used, in order to avoid affecting the impulse ratio the gap should not be greater than 80 per cent of the length of the supporting insulator string.

Method No. 3.—Limitation of the line insulation to earth from points within 100 circuit feet (30 meters) of the terminals of the apparatus to points approximately ½ mi. (1 kilometer) therefrom, to values not in excess of the flashover voltage given in Table I.

Available Data on the Impulse Strength of Transformers

The available data on the impulse strength of transformers may be divided into two general classes, namely, those obtained in the laboratory and those obtained under service conditions.

The natures of the two classes of data are, of course, quite different because in the laboratory a transformer can be tested to destruction, while the data obtained under service conditions have been in the form of "records" covering many years of service. These records show that when connected to transmission lines having certain insulation, transformers receiving a certain dielectric test have successfully withstood lightning voltages. The conclusion is that the impulse voltage strength of the transformers is satisfactory when coupled with line insulation having a certain impulse

*Ratio of impulse to 60-cycle crest voltage arc-over.

arc-over voltage. For example, if transformers receiving a 60-cycle dielectric test of 231 kv. have been operating successfully for many years on a 115-kv. circuit exposed to severe lightning conditions, and the line is insulated with seven 10-in. (25.4-cm.) disks spaced 5¾ in. (14.6 cm.) apart, the flashover value of these line insulators may be used as a "yard stick," indicating the impulse voltage strength of the transformer. This, of course, does not give a numerical measurement of the impulse breakdown strength, but affords a convenient measure of satisfactory impulse strength.

Laboratory tests have proved to be of great benefit in determining the impulse arc-over voltage of insulator strings using various shapes of waves, in obtaining the impulse breakdown of insulating materials such as oil, solids, oil and solids in series as used in transformers, and of complete transformer windings. These tests have brought out the following points:

1. The impulse ratio* of various types of transformer windings is fairly constant for a given wave. The significance of this is that the low-frequency dielectric strength from windings to earth gives a rough measure of the impulse strength (from windings to earth).

2. The impulse ratio of the flashover of insulator strings of different lengths, and of point-gaps of various spacings in air is practically constant for a given wave.

3. The impulse strength of windings which are fully insulated in accordance with the A. I. E. E. Standards (*i. e.*, windings insulated for a test of twice line to line voltage plus 1000 volts) is satisfactory when used with average line insulation used in the United States.

Selection of Line Insulator Disks

Voltage arc-over values of 10-in. (25.4-cm.) insulator disks spaced 5¾ in. (14.6 cm.) between units, have been selected as the standard for expressing the impulse strength of transformers for circuit voltages of 69 kv. and above. Table I shows the general average number of 10-in. (25.4-cm.) disks used on the leading transmission lines in the United States[8] before the practise of over-insulating began.

Yard Stick Used to Express Impulse Voltage Strength of Transformers

Since the impulse voltage strength of transformers as herein defined bears a certain definite relation to the arc-over of standard suspension insulator disks when subjected to various shapes of waves, under both dry and wet atmospheric conditions, it is possible to express the impulse voltage strength of the transformers in terms of disks. It could be specified by definite numbers of disks but disks sometimes vary slightly in length of spacing. Since both the 60-cycle and impulse flashover voltage of insulator strings is, within reasonable limits of lengths, proportional to the total length of the string made up of disks having different spacings, it seemed that the most dependable way of specifying an insulator string that represents a definite measure of impulse voltage is by its 60-cycle arc-over value. It was decided, therefore, to use the 60-cycle *dry* flashover values for "yard-stick" purposes. This results in a very simple and convenient way of arriving at the desired results.

*Ratio of impulse to 60-cycle crest voltage breakdown.

The dry 60-cycle arc-over values of 4¾-in., 5⅛-in., 5¾-in., and 6½-in. spaced disks are given in Table III for reference purposes.

TABLE III

Unit No.	60-Cycle Dry Arc-Over Kv. r. m. s.			
	4¾ In.†	5 ⅛ In.	5 ¾ In.	6½ In.
1*	(78)	(78)	78	(78)
2	120	125	140	155
3	165	175	195	215
4	215	225	250	280
5	260	275	300	340
6	300	320	350	395
7	345	365	400	450
8	385	410	450	505
9	425	455	500	555
10	470	500	550	610
11	505	540	595	660
12	540	580	640	710
13	580	615	680	755
14	615	660	725	805
15	655	700	770	855
16	690	735	810	900
17	725	770	850	945
18	760	810	895	995
19	800	850	940	1040
20	835	890	980	1085

*Flashover of single unit taken as same for each size.
†Spacing between units.

The tabulation in Table I simply expresses the impulse strength of a standard transformer insulated in accordance with the American Institute Standards of Dielectric Test; it places no restriction whatever on the line insulation but rather it suggests suitable transformer insulation for any given adjacent line insulation. For instance, if it is desired to over-insulate the line next to the substation, Paragraph (b) indicates to what extent the transformers should be over-insulated. If, for example, a 230-kv. transformer is to operate on a circuit insulated with 18 instead of the standard number of fourteen 10-in. disks per string, the transformer should be given an insulation test of $461 \times \frac{895}{725} = 570$ kv.

On the other hand, if transformers of the reduced insulation class (built for operation with solidly and permanently grounded neutral and receiving an induced voltage test of 2.73 times line-to-neutral voltage) are used in accordance with the A. I. E. E. Standards, the adjacent line insulation should be reduced in the ratio of $\frac{2.73}{3.46}$. This reduction by coincidence corresponds approximately to the reduction in the adjacent line insulation for the next lower rated circuit voltage.

Recommendations for Balancing the Transformer and Transmission Line Insulation

So far, the method of expressing the impulse strength of transformers only has been discussed. It is quite important, however, that steps be taken by the purchaser to carry out the principle of balancing the transformer and the line insulation. If this is done, then the main part of the transmission line may be over-insulated without increasing the size and cost of the transformer.

Three methods are recommended: namely, (1) the use of an effective lightning arrester, (2) the use of a horn-gap, and (3) the maintenance of average line insulation for a limited distance from the station.

Method 1—Lightning Arresters

The requirement that Method (2) or (3) should always be used in combination with Method (1) is included because quite often the lightning arrester is temporarily disconnected for inspection, overhauling, maintenance, etc., and it is desirable to have something to act as a last line of defense.

Method 2—Horn-Gap

Quite often it is more convenient to use a gap to limit impulse voltages rather than maintaining average line insulation for a distance of one-half mile. This gap is sometimes in the form of spoons, or blunt points, mounted separately from the insulator string. Also, quite often the gap is formed by fastening guard-rings or arcing horns to each end of an insulator string using the insulators as a method of support. All these gaps as well as needle-gaps have practically the same 60-cycle and impulse arc-over characteristics for the same settings.

The gap impulse arc-over values are roughly 10 per cent less than the insulator impulse arc-over values. The reason for this is that except for a direct stroke of lightning at the transformer bank, the half-mile of reduced line insulation should provide better protection than a single gap having the same impulse voltage arc-over, because a wave coming in over the half-mile of normal line insulation will usually be attenuated more than 10 per cent by the time it reaches the station. By this is meant that if a wave comes along whose maximum value is just under the arc-over of the first insulator string, or if it arcs over the first insulation string, by the time it reaches the transformer one-half mile away, its maximum value has decreased at least 10 per cent below the value it had when passing the first insulator. Then, too, the one-half mile of normal line has several earthed points whereas a gap has only one. This should contribute to a little better protection.

It will be noted that the 60-cycle dry flashover values given in Table II are less than the 60-cycle dry flashover voltages of line insulators given in Table I by more than 10 per cent. This is because the impulse ratio of gaps is from 20 to 25 per cent greater than the impulse ratio of suspension insulator strings. Hence, for a gap to have say a 10 per cent less impulse arc-over the 60-cycle arc-over must be from 30 to 35 per cent less than that of an insulator string.

Method 3

The 60-cycle flashover voltage values given in Table I represent even numbers of disks spaced 5¾ in. (14.6 cm.) apart. Consequently, these voltage steps are not in all cases proportional to the circuit voltage steps. The 60-cycle values which correspond in steps to the circuit voltages ignoring whether or not they represent even numbers of disks, would be about as shown in Table IV.

TABLE IV

Rated circuit kv.	Trans. 60-cycle test voltage—kv. r. m. s.	Insulator 60-cycle dry flashover—kv. r. m. s.
69	139	250
92	185	315
115	231	385
138	277	450
161	323	520
196	393	625
230	461	725

The length of the insulator strings corresponding to these voltages would be as given in Table V.

TABLE V

Circuit kv.	Length of insulator string	
	Inches	cm.
69	23	57.5
92	31	78.8
115	39	99.0
138	46	117
161	55	140
196	68	173
230	80	203

From the above it will be noted that the length of the string in inches is roughly one-third the rated circuit voltage.

Where insulator disks have a spacing different from 5¾ in. (14.6 cm.), it is felt that values corresponding to the above, or as near as can be obtained with even numbers of disks, would be the more correct values to use rather than those given in Table I.

Nature of the Recommendations in Part II

These recommendations on balancing the transformer and line insulation are intended to be strictly advisory; they are given simply as a guide for the application of transformers on high-voltage transmission systems, considered from the standpoint of lightning voltages.

Bibliography

1. *Rationalization of Transmission System Insulation Strength,* Philip Sporn, A. I. E. E. Quarterly TRANS., Oct. 1928, p. 998.

2. "Surge *vs.* Impulse Tests for Transformers," *Electrical Wld.*, June 22, 1929, by V. M. Montsinger and J. F. Peters.

3. *Relation Between Transmission Line Insulation and Transformer Insulation,* by W. W. Lewis, A. I. E. E. Quarterly TRANS., Oct. 1928, p. 992.

4. *Lightning*, by F. W. Peek, Jr., A. I. E. E. Quarterly TRANS., 1929, p. 436.

5. *Surge Characteristics of Insulators and Gaps,* J. J. Torok, A. I. E. E. JL., 1930, p. 276.

Discussion

For discussion of this paper see page 1496.

Coordination of Insulation as a Design Problem

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Member, A. I. E. E.

Synopsis.—The factors having influence on insulation design of transmission line and station are briefly reviewed, and it is pointed out that the progress of the art does not yet allow of close design of the insulation structure for insulation strength.

The prominent part played by the lightning arrester is stressed, and the fact that it has a marked effect on the coordination of station insulation.

Examples of a typical 110-kv. station where no coordination was made, and of a 220-kv. station where a deliberate coordination was attempted, are given, as well as the experience obtained with each.

INTRODUCTION

INSULATION design, both for the transmission line and for the various members of the station insulation, has reached its present status largely through experience. The behavior of insulation, when subjected to electric stress, is probably less understood, even today, than any other electrical phenomenon, and as a consequence it has been necessary to apply the acid test of operation in order to determine the suitability of insulation design for the service intended. The almost total lack of knowledge of the magnitude and character of the over potentials appearing on a system has only added to the difficulty of rational design.

Overhead transmission at voltages of 110 kv. and above and for distances of the order of 100 miles and greater has been general for a number of years, and the service given by these systems has been, generally speaking, quite good from an insulation standpoint, considering the lack of knowledge of the behavior of insulation. Where weakness has developed, that part of the insulation structure has been strengthened, and therefore, unconsciously perhaps, a rational coordination of the various members of the insulation structure to the stresses, has resulted.

Several factors appear to have had an influence on the present condition of affairs. In the first place, there has been the desire for increased service security, and consequently attempts to make important lines lightning proof. The result, in many cases has been increase in the line insulation without corresponding increase in station insulation, so that the coordination accomplished through experience has been all upset, —sometimes with disastrous results.

A second factor has been the recent intensive study of the behavior of insulation when subjected to surges, and the parallel study of the magnitude and character of surges appearing upon transmission lines. The data obtained are by no means complete, and conclusions are often contradictory, but the general result has been to make possible, for the transmission line itself at least, a design which can make the line practically lightning proof, if desired. The data for bus supports and station inductive apparatus are not nearly so complete, so that the tendency naturally is, to design the line insulation to give a lightning-proof line, and to assume that the station insulation is satisfactory, in the absence of data to the contrary.

A third factor calling for close study of insulation requirements is the recent increase in practical system voltage to 220 kv. The natural tendency here has been to keep down capital cost of transformation by solidly grounding the 220-kv. neutral and using graded insulation on the transformer. The only justification for the higher system voltage is a decrease in over-all transmission cost, so that any means of accomplishing this with safety is desirable. On the other hand, the amount of power per circuit carried on these high-voltage lines has made it imperative that the line insulation be sufficient to keep outages from flashover to the lowest possible number. These tendencies are in opposite directions, so that some means of coordination must be arrived at. The most direct method would appear to be to increase the transformer insulation strength, but other means are available, some of which are given in detail later.

FACTORS GOVERNING DESIGN

A. Transmission Line. The overhead transmission line is subject either to lightning, switching surges, and surges due to arcing grounds, or to the latter two only. The magnitude of the maximum lightning surge has been quite definitely established to be several times that of the switching surge, so that a line which has ample insulation to withstand lightning surges can usually be considered as safe against all surges that may occur of whatever nature.

The magnitude of the lightning surge is proportional to the average height of conductor above ground if the surge is induced, and the voltage is higher, if no ground wire is used, for the same average height of conductor. The maximum surge potential that the line may assume is also limited to the insulation strength of the insulators for the surge in question. This in itself, is a variable quantity, due to the variation in impulse ratio of the insulators. This applies whether the surge is a so-called direct hit, or an induced surge.

The insulation strength of the string along its length has been determined with some degree of accuracy by laboratory tests, and varies greatly with the duration of the surge, increasing as the duration decreases. The insulator string is therefore, to some extent, self-protecting, as the surges of highest magnitude are usually also of short duration. Fig. 1 shows this clearly; also the effect of grading rings.

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

Minimum insulation strength is not always developed along the insulator string, and arcs sometimes strike from the line end of the string to the tower. The present tendency towards increasing the insulation on existing lines will increase this possibility, and it should be kept in mind when increase in insulation of the line is contemplated.

Table I has been compiled from data on 110-kv. and

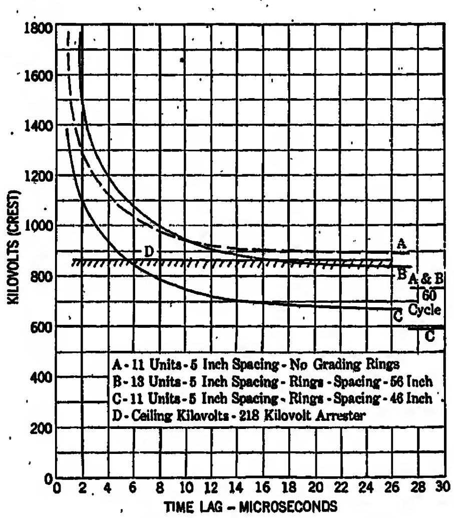

FIG. 1—KILOVOLT FLASHOVER-DURATION CURVES FOR SPILLWAY GAP

220-kv. lines of the Hydro-Electric Power Commission of Ontario, and shows the estimated insulation strength of the lines, at commercial frequency.

TABLE I

Line	Average height of top conductor	No. of insulator units of 5 inch spacing	60 Cycle flashover Dry	60 Cycle flashover Wet
	feet		kv.	r. m. s.
Pelham-St. Thomas steel tower......	58	9	470	340
St. Thomas-Windsor steel tower......	50	8	420	310
Niagara-Dundas steel tower.........	47	8	420	310
St. Thomas-St. Clair wood pole......	29*	7		
Thunder Bay wood pole............	33	7		
Thunder Bay steel tower............	54	8	420	310
Ottawa-Smith Falls wood pole.......	28*	7		
Paugan-Leaside steel tower..........	37*	18	785	608

*Flat configuration. Paugan-Leaside line has two ground wires, all others one ground wire.

The lightning outages on approximately 1000 circuit miles of 110-kv. line equipped with suspension insulators per 100 miles per year are as follows:

1926—2.96
1927—1.25
1928—1.53
1929—2.65

The corresponding figure for the 230 miles of 220-kv. line from Paugan Falls to Toronto for one year of operation (1929) is 1.75.

When the majority of the 110-kv. lines were placed in service, nothing was known regarding the magnitude of lightning voltages to be expected, or of the impulse insulation strength of the insulators, yet these lines have been relatively immune from flashover due to lightning in districts having 25 to 30 storms per year. The outages average less than two per 100 miles per year for all 110-kv. lines, and the line insulation has never been increased.

The 220-kv. line has only been operating one lightning season, and there have been four outages, the cause of which could not be traced. Due to the fact that thunder storm areas were known to be in the vicinity of the line at the time the line flashed over, the outage has been considered as due to lightning. The insulation requirements for this line had been very carefully reviewed before specifying 18 units with 5-inch spacing. From the data available at the time, it appeared that this line should be very nearly immune from flashover due to lightning, but that to make it lightning proof appeared possible only by greatly increasing the insulation. The increase in cost would not be justified by the relatively small increase in service security.

This point cannot be stressed too strongly. It seems certain that with the present types of lines, one or two flashovers per year are bound to occur, in lightning areas, no matter what the design. The cost of towers, as well as of insulation, will increase rapidly if the number of insulator units required to make the line 100 per cent proof are specified. The increase in cost cannot be justified, unless in some very special cases of important tie lines of short length. It would appear to be better to concentrate on means whereby the line may be cleared rapidly, before the power arc can do material damage, and accept the momentary interruption. This may not involve a total interruption in many cases, because of the increasing degree of interconnection of power sources, and the fact that power demands have increased to such an extent that a number of high voltage lines are necessary to serve most districts where service security is of paramount importance.

The transmission scheme suggested in another paper[1] read at this convention can be coordinated easily as to insulation, if the scheme is found practicable from other considerations. With the arrangement suggested, it is possible to accept flashovers on any one high-voltage circuit. If these are cleared instantaneously, as seems to be easily done, so that no conductor or insulator damage occurs, there is no loss of service or increase in maintenance cost. Over insulation of lines is not necessary, and coordination of insulation, other than that normally required heretofore, is not required.

B. Station Insulation. Some measure of coordination of insulation strength among the various members of the station insulation structure is desirable, regardless of whether there is necessity for coordination of the station insulation with line insulation. If flashover is to occur, it is always better that the overstress be relieved at a point where least damage will result. The difficulty is that it is practically impossible to design the various members so that failure will occur for all

1. For references see Bibliography.

types of surges and all conditions at a given location, unless the insulation is so greatly weakened that there is danger of flashover for surges that would be harmless otherwise. It is not sufficient to design so that the oncoming wave will encounter slightly higher insulation as it progresses into the station because possible reflections at points of discontinuity make it necessary to have the insulation greatly stronger at such points. For example, unless the bushing at the line side of an open circuit breaker had at least twice the flashover value of the coordinated line insulation approaching the station, a surge which would just pass this insulation would be likely to cause flashover at the bushing. The assumption is made that the coordinated insulation is depended upon to restrict surges to a value harmless to the station insulation.

Great progress has been made in the last few years in knowledge of the behavior of station insulation when subjected to surges. As a result, the maximum surge voltage which station apparatus may be subjected to without injury will no doubt soon be known, but at present this information is far from being complete. It appears certain that for a few years at least, designers must rely on the sum total of experience supplemented by such reliable information on insulation strength of apparatus as becomes available. This does not mean that coordination of insulation cannot be attempted at the present time, but it does mean that with the data available, too much reliance must not be placed on coordination to give results that will always be effective.

Effect of Lightning Arrester

Fortunately, the same investigations that made possible increased knowledge of insulation strength to surges, also placed the operation of the valve type lightning arrester out of the realm of speculation. It is now possible to state with some definiteness to what value the maximum surge voltage will be limited, with a given arrester. It is, therefore, possible, in the general case, to design the station insulation so that its impulse flashover will be greater than the ceiling voltage of the arrester installed. The term ceiling voltage is defined as the maximum crest voltage at arrester location permitted by the arrester for all types and magnitudes of surges. The impulse strength of bus insulation and to a lesser extent, of high-voltage bushings, is known with some degree of accuracy, but in the absence of such data, a fair approximation can be made on the basis of the 60-cycle insulation strength.

The impulse strength of transformers is still a point regarding which very little is known definitely. Experience with transformers on the lower voltage lines which are protected by lightning arresters, indicates that the arrester having a protective ratio of 3.5 or better will protect the transformer which is designed for standard insulation test against 90 per cent of lightning surges to which it is subjected.[2] It may be concluded that the transformer impulse strength is therefore in the order of at least 2.5 to 3.0 times crest value of system voltage to ground. The coordination of station insulation therefore resolves itself into designing the various parts to have greater strength than the arrester ceiling voltage.

A number of exceptions to the above general condition are evident. In the case of outdoor stations the length of bus may be such that an arrester, if located at the line entrance, may allow surges to pass, of sufficient magnitude to be dangerous to station insulation because of reflections. In these cases, the proper place for the arrester is adjacent to the transformers, as the reflection is usually highest at this point. Bus insulation can be more readily strengthened to take care of reflection at those points where it may occur.

A condition requiring special treatment occurs in those cases where other than normal number of units are required in the arrester stack to protect the arrester against dynamic overvoltage due to loss of load. The ceiling voltage of the arrester is increased in these cases and the protection given is correspondingly decreased. If the increase in ceiling voltage is appreciable, either the insulation strength of the transformer should be increased, or some of the special features of coordination of line and station insulation attempted. It is felt that the former arrangement is preferable, as the latter is still of too uncertain a nature to be depended upon, especially for stations of large capacity.

A third case is one which applies most particularly to some 220-kv. systems, where advantage was taken of a solidly grounded neutral to specify graded insulation. In these cases, it would be expected that an arrester with the normal protective ratio might not be quite good enough to protect the transformer against all surges. Coordination of line and station insulation may then be used as a last resort, or a spillway or protective gap installed, but drastic reduction in insulation strength on the line adjacent to the station appears to be necessary with its attendant difficulties due to line outages.

Two typical cases are tabulated below for stations of the Hydro-Electric Power Commission. The first, given in Table II, is for a 110-kv. outdoor step-down station, protected by lightning arresters, in which no attempt was made to coordinate line and station insulation, other than by specifying for the station, bus insulation which was known to be satisfactory from previous experience in other stations. It may be stated that no failure of transformer insulation due to lightning has occurred and only two or three flashovers of porcelain in any 110-kv. station of the commission. With one exception, lightning arresters have been installed at such stations and an insulation test of twice maximum rated voltage for the transformers has been specified. None of these transformers have graded insulation.

The second case is that of the 220-kv. line entrance and station bus insulation for Toronto-Leaside transformer station. Two banks of transformers were installed in this station in 1928, and as no satisfactory

TABLE II
110-KV. INSULATION. HAMILTON TRANSFORMER STATION

Item	Insulation units	Flashover 60 cycle	
		Dry	Wet
Lightning arrester. Oxide film. Total cells 1168. 3 phase stacks and ground stack. Cells per stack—292		kv.	r. m. s.
Line and bus disconnects..........	2 unit pillar	329	220
Circuit breakers—Line............	110 kv. bushing	345	300
—Transformer.....	132 kv. bushing	400	345
—Transformer.....	110 kv. bushing	345	300
Transformer.....................	110 kv. bushing	345	300
Strain bus......................	10 suspension units 5 inch spacing	515	385

lightning arresters were available at that time, a deliberate attempt was made to coordinate the line entrance and station insulation with the transformer insulation. The transformers had the 220-kv. winding insulation graded, and the standard A. I. E. E. induced test of 2.73 times system voltage to ground or 350 kv. was specified. There are four groups of high-voltage coils and as an additional precaution, the line group of coils was provided with insulation equivalent to that for a transformer designed for 440-kv. test voltage.

The various items of the insulation structure are given in Table III

TABLE III

Item	Insulation units	60 Cycle flashover	
		Dry	Wet
Line from station to point 2 miles out, with 4 ground wires........	14 five-inch, ungraded suspension disks	kv. 665	r. m. s. 520
Disconnecting switch.............	6 unit pillar	645	560
Supported bus....................	6 unit pillar	645	560
Suspension bus...................	20-5 inch, ungraded suspension disks	850	670
Oil breaker bushing..............	Oil filled	585	420
Transformer bushing..............	Condenser—not less than	550	465

In spite of this attempt at coordination, an apparatus insulation failure occurred during a severe lightning storm early in 1929. No evidence of lightning flashover on the reduced line insulation was found.

After the failure, a spillway gap was installed adjacent to the transformers having 13 five-inch disks, and arrangements were made to have an equivalent gap tested in the laboratory, both with and without grading rings. Although a number of storms have occurred since installation of the spillway gap, no flashover of the gap has occurred. However, a continuous record was kept during the lightning season with a klydonograph recorder, and no record of any surge of magnitude sufficient to cause flashover of the gap was obtained.

Lightning arresters are now being installed adjacent to these transformer banks, having an estimated ceiling voltage of 870-kv. crest. The relation of this ceiling voltage to the flashover voltage of the spillway gap is shown in Fig. 1.

One other instance of an attempt at insulation coordination is of interest. A number of 110-kv. potential transformers purchased by the commission in 1924, were built to a specification which required that on test, the voltage be applied to the low voltage winding and raised until flashover occurred on the high-voltage bushing.

These transformers have given satisfactory service, but there is no evidence that they would not have given equally as good performance if the above feature had been left out of the specification.

SUMMARY

The trend of insulation coordination has been indicated and summarized; this trend appears to be somewhat as follows:

1. Knowledge of insulation required for both line and station apparatus has been acquired largely as a matter of experience, and a coordinated system has resulted.
2. Increased line insulation has come about as a result of:
   (a) Recent investigations into behavior of lines and line insulation when subjected to surges.
   (b) Better knowledge of magnitude and character of lightning surges.
   (c) Desire to decrease the number of line outages, especially on important circuits, with relatively high loading.
3. Knowledge of the behavior of station insulation is still such as to allow only very general approximations to be made. The situation is complicated by the very intricate nature of voltage reflections which may occur at points of discontinuity.
4. Station insulation has not been increased because the amount of increase necessary could not be accurately specified, and also because of the difficulty of modifying existing stations to the new insulation design.
5. If the valve type lightning arrester is used, it is a determining factor in station insulation requirements.

ACKNOWLEDGMENT

The facilities of the High-Voltage Laboratory of the Westinghouse Electric and Manufacturing Company at Trafford were used to obtain the data shown in Fig. 1. It is a pleasure to record the cooperation of engineers of this and other organizations in studies of our insulation problems.

Bibliography

1. Ackerman, P., *The Problems of Service Security in Large Transmission Systems.* A. I. E. E. Summer Convention, Toronto, Canada, 1930.

2. Atherton, A. L., "The Ideal Lightning Arrester," *Electric Journal*, Aug. 1929, page 366.

3. *Relation between Transmission Line Insulation and Transformer Insulation*, W. W. Lewis, TRANS. A. I. E. E., Oct. 1928, page 992.

4. *Rationalization of Transmission System Insulation Strength*, Philip Sporn, TRANS. A. I. E. E., Oct. 1928, page 998.

Discussion

For discussion of this paper see page 1496.

Standards of Insulation and Protection for Transformers

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and

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Synopsis.—This paper presents the reasons and the evidence which have influenced the authors to favor the proposed Recommendations on Relation of Transformer Insulation to Adjacent Line Insulation set forth in a companion paper by Messrs. Montsinger and Dann.

The paper first outlines the principal considerations which govern the determination of transmission line insulation on the one hand and transformer insulation on the other, and concludes that the line insulation is a service problem requiring a unique solution whereas the transformer insulation is a manufacturing problem requiring a standardized solution. True co-ordination of the one with the other therefore seems impossible, indicating the need for protective measures at the point of contact.

Considerations affecting the selection and characteristics of such protective measures are discussed briefly and the reasons outlined for believing that, at present, service experience is a better criterion than research tests upon which to decide such selection.

Twenty-five years' service experience on the system now controlled by the Buffalo, Niagara and Eastern Power Corporation, with protective gaps similar to those recommended as one of the proposed protective measures, is described and the conclusion drawn that the use of such gaps under suitable conditions constitutes a satisfactory protective measure.

* * * * *

THIS general subject was first brought to the attention of the Institute in a formal way by two papers[3,4] presented in 1928.

Following the presentation of these two papers, the question was referred to the Transformer Subcommittee of the Electrical Machinery Committee. After long consideration this subcommittee formulated for insertion into the Institute Standards for transformers a proposal defining the conditions, with respect to surge voltages, under which standard transformers might safely be operated. The proposed provisions are included in the companion paper by Messrs. Montsinger and Dann.

The problem has been precipitated by the trend toward higher standards of transmission line insulation than prevailed at the time the present standards for transformer insulation strength were adopted, and takes the form of a question whether transformer insulation strength should be increased, or transformer protection standardized.

The purpose of this paper is to record some of the considerations which influenced the writers, one of whom is a member of the Transformer Subcommittee, to favor the proposed method of dealing with this situation. These considerations relate, first, to certain factors which appear to govern the rational choice of line and transformer insulation strength, and second, to operating experience with a system of protection similar to one of those proposed. No claim is made for originality, but it has seemed worth while to record the argument in order to help clarify the situation and crystallize opinion.

Considerations Governing Selection of Line Insulation

It is now universally recognized, of course, that long transmission lines must be insulated against lightning rather than merely for the operating voltage if they are to render acceptable service from the standpoint of continuity. Just how strong the insulation should be is a unique economic problem in each particular case, governed by a number of factors.

In a territory subject to a given statistical number of lightning storms per year producing a given number of discharges per unit of area, the number of outages occurring on a given transmission line will be a function of two factors which may be broadly and briefly stated as (1) strength and (2) length. The number of interruptions per year on a given line, other things being equal, will be in proportion to an inverse function of its insulation strength and a direct function of its length. We have become accustomed during the past few years to sum up the insulation performance of a transmission line in terms of flashovers per mile per year, but unfortunately the standard of service to customers dependent upon the continuity of the line, which is the basic determining factor, depends not upon the number of interruptions *per mile* per year, but upon the *total* number of interruptions per year. Thus it follows that if equal service is to be rendered by lines of unequal length, the insulation strength must be varied in inverse proportion to the length of the line. A ten mile 66-kv. line insulated with four standard 10-in. disks will almost certainly give more continuous service than a hundred mile line insulated with eight disks.

Thus it is apparent that length is one factor entering

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3. *Relation Between Transmission Line Insulation and Transformer Insulation*, W. W. Lewis, A. I. E. E. TRANS., Vol. 47, Oct. 1928, p. 992.

4. *Rationalization of Transmission System Insulation Strength*, Philip Sporn, A. I. E. E. TRANS., Vol. 47, Oct. 1928, p. 998.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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the rational design of transmission line insulation for a given service requirement.

Another factor which bears on the question is whether it is the only line supplying the load or whether there are other lines supplying the same load either from the same source or from different sources. It is obvious that for a given quality of service to the customer, a single supply must be better insulated than a properly relayed multiple supply.

Another set of factors involved is the frequency and severity of storms in the territory traversed by the line. A line traversing territories differing in these respects may have its insulation varied accordingly. Of similar import is the profile of the right of way or of the line itself. A high river crossing for instance, is often more heavily insulated than the remainder of the same line.

Still another factor is that of earth conditions, which may affect not only the level of the conducting plane with relation to the transmission wires, but also the resistance of the tower foundations to earth, both of which may, in appropriate circumstances, affect the frequency of flashover of a given insulation.

The presence or absence of ground wires and other protective devices is still another factor of importance.

The above are believed to be the principal factors controlling the rational design of line insulation and it will be observed that they all relate to the particular circumstances surrounding each individual problem.

Considerations Governing the Selection of Transformer Insulation

In the first place, it is obvious that transformers connected to overhead transmission circuits must be built to withstand lightning surges in some degree. The only question is as to the degree of strength which they should possess. There are three alternatives: (1) the transformers may be built to withstand the maximum surges which they can receive from any line, or (2) the transformers may be built "special" for each installation to withstand the maximum surges which can be received from the actual transmission lines, or (3) the transformers may be built to withstand surges of a definite maximum amount and protected against surges of a higher value.

Under the first alternative it would be necessary to build all transformers to withstand direct strokes of lightning. It seems obvious that if this were possible at all its cost would be quite uneconomic and entirely out of the question.

Under the second alternative since practically every transformer built would have different conditions to meet they would all be different, and standardization of transformers would, of course, have to be abandoned. Moreover, conditions might change with time and transformers originally installed to supply short lightly insulated lines, for instance, might later be called upon to supply long heavily insulated lines, for which they would not be adequate. That this alternative would result in chaos and would be entirely unworkable is too obvious to require further discussion.

We are therefore forced to the adoption of the third alternative, namely, the standardization of transformer insulation to withstand surges of limited magnitude. This also involves the problem of protecting the transformer against surges of greater magnitude than it is designed to withstand. Both of these problems, it should be observed, are questions of standardization.

To sum up, it is evident that the transformer is a manufacturing problem and calls for a standardized solution, whereas the line is a service problem and demands an individual solution. Co-ordination between the two, therefore, appears quite impossible.

There are two ways in which the strength of the transformer insulation might be fixed. One way would be to determine the characteristics and magnitude of the lightning surges to which transformers are subjected, devise ways of reproducing such surges in the laboratory in order to learn the surge resisting properties of insulation, and then use these data to design transformers to withstand such surges. Another way would be to build transformers and put them in service where they are subjected to the actual lightning surges and learn by experience. This method is perhaps less scientific, but lightning surges and insulating materials, and our knowledge of them being what they are, it seems likely that this method would result at least as well and possibly better than the more scientific method. As a matter of fact, this is the method which has been largely followed in the past and has resulted in our present transformers

The next question is whether the present standards for transformer insulation are satisfactory or whether new standards possibly more closely related to the higher average strength of modern transmission line insulation should be adopted. Since many millions of kv-a. of transformers built under present standard specifications are already giving satisfactory service there would seem little point in now establishing a new standard at a different level, especially as protection against surges of greater magnitude than the transformers would be designed to withstand would always be necessary, regardless of the actual level of insulation strength chosen as standard.

Protection of Transformer Against Excessive Lightning Surges

If this conclusion is accepted, the problem still remains of protecting the transformer against surges too severe for it to withstand. Again there are two ways in which we can proceed. The first alternative is to specify exactly the magnitude and characteristics of the maximum surges which the transformer will withstand, leaving the user to determine as best he can the required protection. This alternative demands intricate scientific knowledge of natural surges and of the behavior of insulation, which is not now and may never be completely available.

The second alternative is to standardize the characteristics of protective devices. Such devices may be much simpler and their characteristics much more easily determined and more closely controlled than those of the transformer and therefore may lend themselves much more readily to standardization with respect to surge voltage characteristics. Such devices may be separate pieces of equipment, or may be a part of the transformer.

Such protective devices may be selected not only with reference to the characteristics of the transformers but also with respect to the requirements of the service. For instance, if the service requirements should make it necessary that the transformer be protected against surges without interruption of the circuit, then a protective device of one character may be indicated. If on the other hand, the service requirements should be such as to permit an interruption of the circuit to protect the transformer, then a somewhat different and possibly less costly device may be justified.

Having come this far, one more question remains, namely: Is the protection of standard transformers against lightning surges a proper subject for Institute standardization? It seems to the writer that it is. Certainly it is if the protective device is made a part of the transformer. In any case the surges to which a transformer is subjected are a part of its environment in the same sense that the elevation, ambient temperature, weather exposure, and circuit current and voltage conditions are parts of its environment. The Institute Standards do not hesitate to specify the limiting conditions, in these other respects, to which the transformer is adapted, and there would seem to be no reason why they should not also specify the limiting conditions as to lightning surges.

If this is conceded, then again we are faced with the choice of either the scientific or the practical procedure. Again we find that the scientific procedure involves knowledge which is not available, whereas the practical procedure can be based on simple laboratory tests and on experience which can be demonstrated to have given satisfactory results.

The remainder of this paper is a brief account of the development on the system of the Buffalo, Niagara and Eastern Power Corporation of a simple protective scheme which is now generally used on this system and has behind it a record of some twenty years or more of satisfactory operating experience. This experience demonstrates that such devices will give adequate protection to transformers without themselves causing unnecessary interruptions.

Experience with Protective Gaps

When the first 60-kv. transmission line was constructed across the western half of New York State between Niagara Falls and Syracuse in 1905 and 1906, it was necessary to work out some scheme for the protection of the terminal apparatus against lightning and switching surges.

The original arrangement designed by R. D. Mershon consisted of three horn gaps on each phase wire. These horn gaps with different settings were mounted on single poles with the phase wire carried across the top as shown in Fig. 1. On pole *C*, or the one nearest the station, the gap was set to flash over at a value of 45,000 volts to ground and the ground current passed through an open fuse wire of No. 20 B & S copper 15 ft. in length mounted between insulators on the side of the pole. On pole *B* the intermediate gap was set to flash over at 67,000 volts to ground. The current in this path to ground passed through a series of carbon resistance rods mounted on the side of the pole on 33-kv. insulators. The resistance in the ground lead was designed to be 20,000 ohms. On pole *A*, or the one nearest to the line, the gap was set to flash over at 115,000 volts to ground and the ground current passed through a resis-

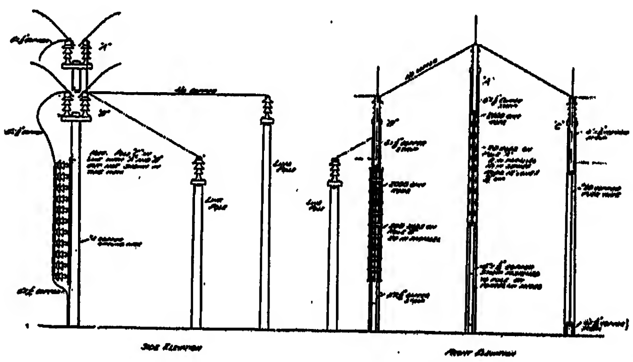

Fig. 1—Original Lightning Protection Equipment of Niagara, Lockport and Ontario Power Company—Installed 1905

tance of 100 ohms made up of carbon rods and mounted in the same manner as on pole *B*.

At the time of construction some structures located in particularly exposed locations were equipped with gaps to ground on each phase wire. These were arranged by mounting a cap of cast iron on the pin type insulator supporting the line. This cap was drilled to take one horn of the gap, and the other horn made of a curved angle iron, was attached to the grounded part of the structure itself. The purpose of the grounded gaps on the line structures was, of course, to prevent damage to the insulators at these exposed points. Interruptions were necessarily experienced when a flashover occurred but when flashovers occurred on these structures, the lines could be cut back in service.

Trouble was experienced with the carbon resistance rods on the original station gaps and the design was changed in 1909, using heavy carborundum rods. These rods were 3⅛ in. in diameter and 7 ft. 6 in. long and were mounted on insulators on the side of the pole. Three rods in parallel were used as a resistance for each gap as shown in Fig. 2.

Experiments were made during 1909 with concrete

resistances made up of a series of concrete blocks. These seemed to work about as well as the carborundum rod resistances and installations of both types were made and put in operation.

In 1920 the design of station horn gaps was changed to

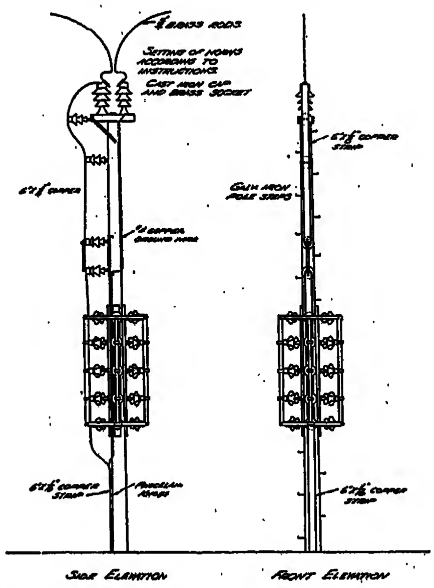

Fig. 2—Modified Form of Lightning Protection Used by Niagara, Lockport and Ontario Power Company—Installed 1909

make a much simpler and smaller structure. At this time the gaps for the three phases were mounted on one structure and the resistance grounds eliminated. The construction adopted was as shown in Fig. 3 and in

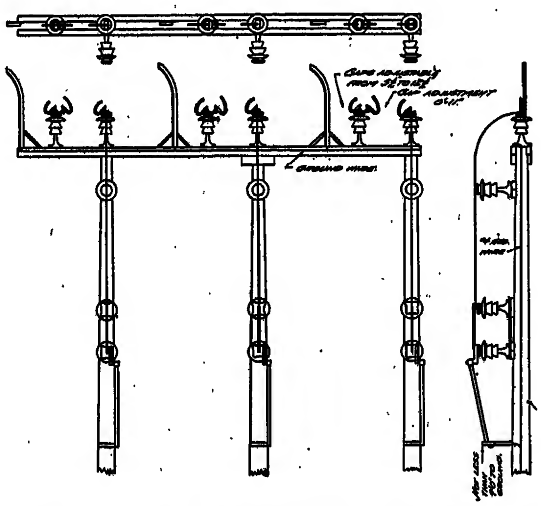

Fig. 3—Present Form of 60-Kv. Station Lightning Protection Used by Niagara, Lockport and Ontario Power Company—Adopted 1920

Fuse gap 7 in.; 75-kv. 60-cycle flashover. Ground gap 10 in.; 100-kv. 60-cycle flashover

general, this type of construction is in service today. The insulator supporting the line wire is equipped with two horns as shown. Another insulator mounted adjacent to the line insulator supports the horn making up the fused or smaller gap and this horn is connected through a disconnecting switch and expulsion fuse to ground. The fuse tube used is made up of a 1½-in. O. D. micarta tube with a ¾-in. bore 6 ft., 6 in. long bound with torpedo twine. The fuse wire used is No. 26 B & S copper. The dead ground gap is made up of a bent angle mounted on the structure itself and thoroughly grounded. On the 60-kv. system the fused gap is normally set at 7 in. and the dead ground gap set

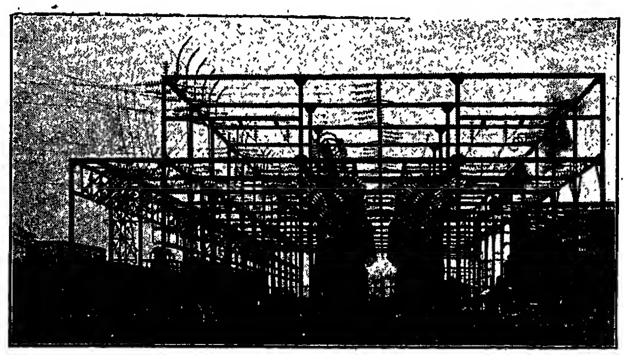

Fig. 4—John L. Harper Station of The Niagara Falls Power Company Showing Safety Gaps on 60-Kv. Structure

at 10 in., corresponding to 60-cycle flashover values of approximately 75,000 and 100,000 volts.

The type of construction shown in Fig. 3 has been built in several forms: mounted on both wood and steel poles, with two and three poles for the supporting structures, with standard pin type and post type insulators, and with a hinged fuse tube eliminating the disconnecting switches. At the newer and larger 60-kv. stations, the dead grounded gaps are mounted on the top of the structure as shown in Figs. 4 and 5.

On the 110-kv. system the same general type of con-

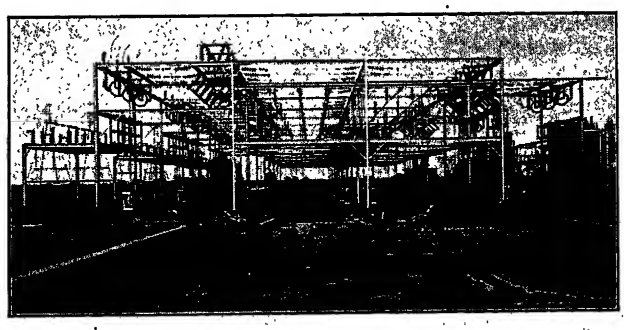

Fig. 5—Norman R. Gibson Station of The Niagara Falls Power Company Showing Safety Gaps on the 60-Kv. Structure

struction has been used, except that the spacing and insulation have been increased. On the main 110-kv. structures, which are made up of latticed beams and columns, the gaps have been mounted on top of the main structure as shown in Fig. 6. In this case the fuses are mounted near the ground on a separate beam and are hinged so that no auxiliary disconnecting switches are needed.

The gaps on the 110-kv. system are set at 13 in. and

18 in. corresponding to 60-cycle flashover values of approximately 150,000 and 250,000 volts.

The proper gap settings have been determined largely by experience. On the 60-kv. system operating at 25 cycles, the switching surges are not severe and only slight changes have been made since the first gaps were put in service. On the 110-kv. system the first gaps were installed in 1925 when the entire system consisted of two parallel lines 40 miles in length. The gaps were first set at 11 and 14 in., but it was found that switching under some conditions would cause the fused gaps to arc. The gaps were then increased in length to 12 and

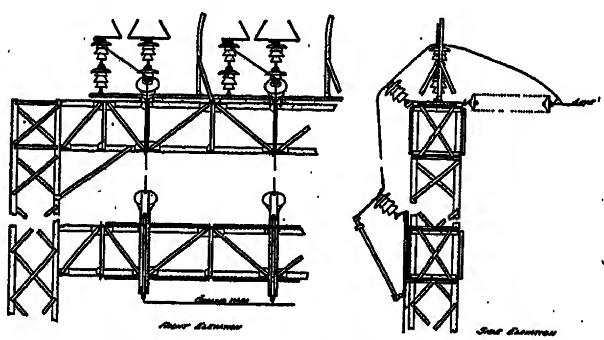

FIG. 6—PRESENT FORM OF 110-KV. STATION LIGHTNING PROTECTION USED BY NIAGARA, LOCKPORT AND ONTARIO POWER COMPANY

Fuse gap 13 in.; 150-kv. 60-cycle flashover. Ground gap 18 in.; 250-kv. 60-cycle flashover.

15 in. and no trouble was experienced until the system became more extensive and the length of circuits switched at one point became greater. It was finally found that with settings of 13 and 18 in., no trouble resulted from switching and the records show that no failures of equipment connected to the 110-kv. system have occurred.

On both the 60-kv. and 110-kv. systems the operation of the horn gaps has been very successful in protecting the terminal equipment since there have been practically no failures during lightning storms. There have been many cases where the fused gaps arced over, blowing the fuses without arcing across the wider settings of the dead grounded gaps. In most cases when the dead grounded gaps have arced over, the breakers controlling the line have tripped, but since practically all main stations or points of delivery are supplied over two or more circuits, interruptions have not followed.

During the progress of this development the line insulation has been progressively strengthened to withstand lightning surges and give the required character of service. As a result, both 60-kv. and 110-kv. long distance lines now carry the same standard insulation of seven units, though certain short 60-kv. lines are operating entirely successfully with four units. In all cases the standard line insulation is maintained right to the station structure.

Comparison of the above safety gaps with those proposed by the Transformer Subcommittee for insertion in the Standards, as shown in tabulation below, reveals that the gap flashover voltages actually used on the system described, are considerably lower than those recommended as standards.

TABLE I

COMPARISON OF B. N. & E. PRACTISE WITH PROPOSED STANDARDS

60-Cycle Dry Flashover Voltages

Nominal line kv.	Proposed standard gaps kv.	B. N. & E. system flashover kv.		
		Line insulation	Fused gaps	Ground gap
69	185	255 (4 units)	75	100
69	185	400 (7 units)	75	100
115	300	400 (7 units)	150	250

Since the evidence of actual operation shows that the smaller gaps do not cause unnecessary interruptions, it is obvious that the recommended gaps will not do so under like conditions. On the other hand, in view of the relatively complete knowledge of the surge characteristics of gaps, there would seem to be no doubt that the recommended gaps will give adequate protection to the transformers.

Discussion

For discussion of this paper see page 1496.

Essential Factors in the Coordination of Line, Station and Apparatus Insulation

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Fellow, A. I. E. E. — Member, A. I. E. E.

Synopsis.—*Generated, switching, and lightning surge voltages all influence the design and application of insulation. The first two might logically be taken as the bases for determining the minimum insulation levels at stations; also, for lines where lightning is not encountered. Since lightning voltages affect service primarily through their influence on lines, the insulation strengths suitable for the lines may bear little relation to the insulation strengths of the stations.*

Several lightning insulation levels are proposed for the coordination of line, station, and apparatus insulation; the basic or lowest level (determined by consideration of generated and switching surge voltages), being established by the line insulation or spillway gaps at the line station entrances, when the line is at a higher level; the busses and connections would constitute the next higher level; the apparatus bushings next; and finally, the apparatus internals.

More complete data on the nature of transient voltages as they originate and are modified by the circuit, and the performance of insulation with these voltages applied, are required before insulation can be coordinated with assurance. During the interim it should be possible to accomplish substantial improvement to service by applying to specific cases as they arise, the knowledge and data already available and being gathered, along the general lines proposed in the paper.

I. Introduction

The insulation of electric circuits has been prominent among the problems commanding the attention of investigators, manufacturers, and operators since the beginning of electric service. In light of the new knowledge being acquired concerning transient voltages as they are imposed upon insulation, the performance of insulation and its application to power systems are now receiving renewed consideration.

It should be distinctly borne in mind that the term "Insulation," wherever used subsequently in this paper, is confined strictly to features of insulation surface strength and does not treat of those qualities of materials and design which control efficiency of manufacture, dielectric strength against puncture, and life; insulation satisfactory in these respects is assumed. It should also be understood that in applying the ideas proposed, economics and similar considerations must be taken into account.

Present practise for line, substation, and apparatus insulation has grown up largely through actual operating experience augmented by theoretical conceptions, research, and tests using in the main test voltages of 25 and 60 cycles, together with rather meager data on transient over-voltages. Due, however, in large part to the incomplete fundamental knowledge of the nature of transient voltages and of the corresponding performance characteristics of conventional insulations, many inconsistencies and variations exist. But it now seems probable that insulation layout may soon be placed on efficient and economic bases, well in advance of its somewhat haphazard present state.

Three general types of voltages are encountered by power system insulations, namely; normal frequency generated voltages; switching and system disturbance transient over-voltages; and lightning voltages. Insulating for generated voltage is quite well understood; insulating for switching surges is not a serious problem; but lightning is still uncontrolled, and no practicable amount of insulation seems adequate in itself to sustain the more severe lightning voltages.

Since station equipment and terminal connections are concentrated and need represent only an extremely limited direct exposure to the influence of lightning, switching surges, or those transients arising within the circuits, may logically be taken as determining minimum or basic insulation levels. On the other hand, lightning voltages which bear no relation to generated voltages usually originate on, and influence service, by affecting the performance of lines, so that in lightning territories the line insulation may be determined from the consideration of lightning. Suitable insulation strengths for lines and for terminal equipment, therefore, may not bear any direct relation, one to the other. The two, however, must be coupled in an effective manner.

It is too early to predict conclusions as to the finally applied results from the present intensive lightning investigations, but it is easy to conceive of quite radical modifications being made in the design and application of insulation during the next few years. For this reason, caution may well be observed in the establishing of standards of insulation practise and methods of testing; rather, the task of obtaining fundamental data should be stressed and the new knowledge, as fast as it becomes available, be applied in the most constructive manner possible.

The following, therefore, is intended to treat of the more essential factors as they now appear, pertaining to the selection, application, and coordination of power system insulation.

II. Insulating for Generated Voltages

Over-voltages from generators are imposed upon insulation due to line regulation, overspeed, over-

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

excitation, and faults on ungrounded systems. The maximum probable generated voltage, and the condition of the surface of the insulation due to weather and contamination may, in some cases, but not generally, determine the minimum amounts of insulation required for apparatus, stations, transmission and distribution lines. Under some conditions outdoors,—such as near cement mills, chemical plants, paper mills, or along seacoasts,—unusual amounts of insulation may be required and in extreme cases, it may not be economically practicable to provide sufficient porcelain leakage surface to overcome contamination, thus making necessary the alternative of periodically cleaning the insulators.

In arriving at the insulation requirements for generated voltages, insulator deterioration and loss of insulation due to physical damage, either from extraneous causes or flashovers, are factors to be considered. The former, however, is not the serious problem that it was several years ago when it was common practise to install several more insulator units in the strain position than in suspension, because of the more rapid depreciation of the former. Now, one, or possibly two, additional units are advisable to increase the insulation strength of the strain string above the normal insulation to give a margin against flashover at the more vital insulator units. Extraneous causes, such as malicious damage, animals and birds, are frequently an important factor in selecting the amounts of insulation and clearances, particularly in the lower voltage classes.

Another important consideration in the selection of the type, (and possibly the amount of insulation), is radio interference, as it has become essential that power circuits be adapted to successful radio coordination.

Only under unusual conditions would it be expected that generated voltages would determine the amounts of insulation which are satisfactory in actual service, as such voltages are considerably lower than switching surges. When insulator contamination is the controlling or a major factor, operating experience and tests simulating the particular conditions encountered seem to be the best guides in selecting the amounts of insulation.

III. Insulating for Switching and System Disturbance Surges

Recent investigations and theoretical considerations indicate that over-voltages may originate within the circuit having maximum values of five to six times the normal circuit crest voltage to ground. The nature of these surges and their magnitudes have not been fully determined though they appear to have the characteristics of damped high-frequency oscillations. The performance of conventional types of line insulators and apparatus insulation has not been sufficiently investigated to be positive regarding their failure strengths with these types of voltages applied. From the information available, however, it seems reasonable to assume that these voltages are of sufficiently long duration to take on some of the characteristics of 60-cycle voltages so far as failure values are concerned. It may even be possible that because of the marked changes in distribution of stresses in the insulation with frequency, and the fact that these surges may be superimposed upon the normal frequency voltage, conventional insulations will fail at lower values for some types of switching surges than for 60-cycle voltages. If this reasoning is correct, the minimum strengths of insulation required to sustain switching surges would be five or six times normal generated voltage to ground with the insulation in its normal operating condition. Experience would appear to indicate, however, that if lightning voltages are eliminated from consideration, insulation having 60-cycle wet flashover values considerably lower than this has performed successfully. Whether this has been due to diversity whereby the maximum switching surge has not occurred with the insulation in its worst condition, or because of assigning an incorrect cause of flashover, cannot be stated. It is not an uncommon experience to have a line trip immediately upon being energized and then stay in on the second or third trial. For such cases it has usually been assumed that the fault which caused the original interruption still existed but it may have actually been the switching surge causing flashover of the damaged or even the unimpaired line insulation. Also, many interruptions are listed as "cause unknown" or "faulty relay action," some of which might have actually been caused by these internal transients.

More complete and careful investigation along the lines of determining the nature of switching surges and the characteristics of insulation under these voltages would seem essential. The influence of present trends toward higher speed switching on the magnitudes of switching surges should also be taken into consideration. These data are of prime importance, because the maximum values of transient over-voltages originating within the circuit may logically be used as the basis for establishing insulation levels for stations and station equipment.

IV. Insulating for Lightning Voltages

Lightning voltages attain higher values than any of the other voltages which insulation is called upon to support. The problem of insulating lines and equipment to give the best, or even acceptable, service is at the present time in a speculative state. The magnitudes and nature of lightning voltages have been only partially determined, though investigations in progress bid fair to accomplish this within the next few years. In general, records obtained to date have been measurements of the insulating strengths of various types and amounts of insulation under lightning surges, and of the characteristics of lightning voltage waves as they appear

traveling on lines. There seems little prospect of completely solving the problem until more fundamental data are obtained and there has been opportunity to confirm them by experimental application.

On the assumption that both induced and direct lightning strokes affect line performance, there would seem to be at least three methods of attack for their control: first, the diversion of direct strokes before contact with the conductors and provision of sufficient insulation to support the maximum induced voltages; second, similar to the first, except for the combination of conventional overhead ground wires and less insulation for the induced voltages; and third, provision of means of discharging the lightning appearing on the conductors without generated current follow up. In addition to these are the present compromise methods for minimizing the number of flashovers and their influence on service, including provision of effective amounts of insulation in combination with conventional overhead ground wires, increase of the lightning insulation strengths, and improvement in switching and relaying. Since lightning magnitudes bear no relation to the operating voltages of the exposed circuits, insulation strengths to restrain lightning will be quite independent of normal circuit voltage.

An analysis of present practise will show wide variations in insulation strengths of lines to lightning voltages even for those operating in comparable territories. To a large extent, these can be accounted for, by the repeated attempts of engineers to improve performance by applying greater and greater amounts of insulation, or the utilization of wood, either intentionally or accidentally, in the quest of satisfactory lightning insulation for the lines. These conditions illustrate present and possible future variations in line insulation practise. They further indicate that present practise cannot be averaged or taken as a criterion of what the final solutions may be for the line insulation problem.

If maximum generated and switching surge voltages are used as the bases for determining the amounts of insulation for lines and terminal equipment, their insulation strengths should be similar. On the other hand, if lightning control is the basis for the line insulation strength, and switching surges for terminal equipment, no particular relation may exist between line and station insulation levels. However, the two must be brought together in a manner to avoid any injurious reaction of either on the other.

V. Coordination of Line, Station and Apparatus Insulation Strengths

Since it is not practicable from present knowledge completely to safeguard service against lightning voltages, it would seem essential as an interim procedure, that the component strengths of the insulation along the circuit be so selected and coordinated that voltages, which do exceed the extablished insulation levels will find relief by spilling at chosen locations where no damage will result or it will be minimized.

Viewed from the standpoint of service,—to accomplish this for the substation and terminal facilities, four insulation levels, each having a suitable margin over the next lower, are proposed, as follows:

The basic, or lowest insulation level would be the line entrance to the station, the insulation strength of this level being set at a value having a safety margin above the maximum switching or similar surge. When differing from the line insulation level, this line entrance section would be equipped as a free spillway, capable of repeatedly discharging excess surges of any kind without damage, whether originating within or without the station.

The next higher insulation level, or second defense, would be the busses and bus connections.

The next higher insulation level, or third defense, would be apparatus bushings.

The highest insulation level would be the internal insulation of apparatus, thus placing this most expensive and most difficult to repair portion of plant in the position of maximum security against over-voltage, and rendering each item of apparatus self-protecting in itself.

For stations where the integrity of the main busses is of major importance, on account of inability to take them out of service for inspection and repairs, or their failure seriously affecting service, these busses might well be placed in the highest insulation level.

With the foregoing voltage levels throughout the station separated by proper intervals, it is believed that excess voltages of any nature encountered at the station will find relief at the spillway sections at the line entrances. It is assumed that direct strokes of lightning to the power conductors within a station will be avoided by utilizing the supporting structures, perhaps reinforced by grounded overhead cables, as diverters.

For the line, the source of lightning surges and seat of lightning flashovers, the insulation level would be determined by the conditions specific to each individual situation, and set at any requisite value quite independent of the levels established in the stations and terminals to which the line connects. In localities without lightning, the general insulation level of the line might be the same as that of the spillway section at the line entrance to the station.

Fig. 1 represents these insulation level relations diagrammatically.

To determine what the insulation levels should be, also the intervals between levels, will require much more data than are now available. These include the nature of surge voltages with their reflections, attenuation, absorption, modifications in magnitude and character due to changes in the electrical constants of the circuit, the characteristics of insulation with these voltages applied, as well as operating experience.

Proper intervals between the levels will be considerably influenced by physical arrangement; for example, in the case of extensive switchyards, it might be possible that negative intervals would be ample for incoming surges; but this would hardly be the case for lightning voltages originating at the terminals. On the other hand, in simple stations of relatively small dimensions and with no branch circuits, large intervals may be necessary.

Even though definite values for these intervals between insulation levels cannot be intelligently assigned at this time, nevertheless, pending more dependable knowledge of the problem, approximately 10 per cent between the spillway at the station entrance and the bus and 5 per cent between bus and apparatus bushings are proposed for trial to advance the experience on this point. These intervals represent the minimum separations between the impulse sparkover curves for the various insulators and spillway gaps, determined by the application of a range of waves giving impulse ratios extending from the higher values

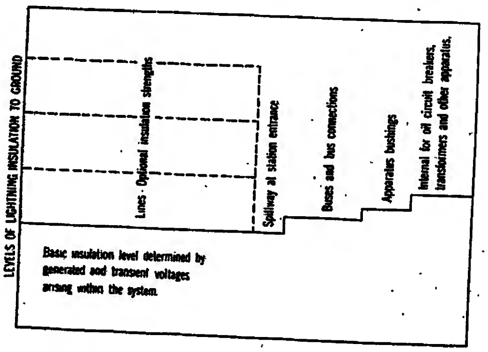

FIG. 1—DIAGRAMMATIC ILLUSTRATION OF RELATIVE LIGHTNING INSULATION STRENGTHS

to approximately unit, or between volt-time curves covering a similar range.

It must be recognized that the foregoing proposals are not free from conjecture. However, meager experience with installations where the insulation has been so coordinated from the limited data on insulation characteristics available gives promise of quite satisfactory results. At least it may be stated in general that, where insulation flashovers due to lightning voltages have been experienced, they have occurred at points which, upon analysis, appear to be weak. These weak points are frequently at locations where failures are most injurious.

It may not always be practicable to obtain the desired grading of insulation levels by selections from present standard insulators; also, if contamination is a controlling factor, the amounts of insulation capable of supporting the low-frequency voltages may have impulse insulation strengths higher than desired for apparatus safety. In these cases, relief gaps might be employed at one or more levels.

As in the past, manufacturers of insulators and manufacturers of bushings may be depended upon to recognize their important position in this problem and to be alert to progress in this branch of the art. They will be able to contribute much in the way of molding their scheduled standards to facilitate the selection of suitably related types and sizes for satisfactory coordination.

Variations from this basic plan of insulation coordination must be expected. For example, for economic and practical reasons, some types of apparatus may have inherently low insulation strengths to lightning voltages as encountered in suitably insulated stations. In such cases there may be an additional problem of providing protection specific to, and supplementing, the insulation of the apparatus.

So long as lightning voltages of magnitudes beyond practicable control must be dealt with, occasional discharges at the spillway gaps as proposed must be accepted; but these should occur without injury to station apparatus and insulation. However, with these gaps spilling freely in air, service interruptions will result. There is then a strong need for a simple and efficient barrier to normal frequency follow-up current to place in these gaps without impeding the unrestricted discharge of the lightning surge, even though its origin be at the spillway. Such devices are not as yet available.

VI. Data Required for the Coordination of Insulation

More complete fundamental knowledge of the nature of transient over-voltages originating within the circuit, and especially of lightning voltages at their origin upon circuits, is essential in order that the characteristics of insulation under these voltages may be fully investigated. This work is progressing, though it must be realized that it is a large task and time will be required for the development of instruments and technique, as well as for the actual accumulation of the data.

In the laboratory, complete volt—time characteristics of the various types and sizes of insulation must be obtained, both clean and as influenced by weather conditions, for the full range of wave shapes encountered from 60-cycle to the steepest lightning impulse. Systematic and uniform methods for this insulation calibration such as methods of voltage measurements, humidity, barometric pressure and temperature, must be developed and applied. Finally these characteristic data should be a part of the manufacturer's catalogued information on insulators and bushings.

Volt—time characteristics of air clearances, such as may obtain between conductors and grounded parts of structures and those which may be used for spillway gaps, are also a necessary part of the data.

New knowledge obtained from lightning research work as it progresses may materially modify present ideas, and extend the scope of investigations and tests.

Even before these researches have been completed, data as they become available, can doubtless be applied to advantage in improving insulation designs and practise. Operating experience from such improved designs, and from existing installations, will be of demonstrating value.

These further investigations of lightning and other extraneous surge voltages encountered in power circuits as at present, can best be carried on cooperatively between the operators of the power systems and the manufacturers equipped with suitable research facilities. On the other hand, as in the past, the facilities of the high-voltage laboratories must be looked to for the insulation calibration work.

During the interim, until more complete insulation characteristic data are available, limited use of the conventional 10-in. diameter suspension insulator as an insulation strength yardstick may be expedient. However, as a standard of reference it is an undesirably crude device since the characteristics of various types of insulation evidently do not remain in similar relation over the range of transient voltages met with in practise. Length of air-gap might be a more suitable substitute for the insulator string as an interim reference standard.

Very substantial results have already been accomplished in the investigation of insulation characteristics. Testing facilities are well established. Many data have been obtained and although somewhat scattering and incomplete, can be used to advantage. Notable among these contributions are: the early work of F. W. Peek, Jr., the results of which were published in Franklin Institute papers, this work being supplemented and extended from time to time, and summarized in his paper on *Lightning*, A. I. E. E. TRANS., Vol. 48, April 1929, p. 436; the investigations by K. B. McEachron on the volt—time characteristics of insulation, also article by E. J. Wade and G. S. Smith on the subject of "Time Lag of Insulators," *Electrical World*, Aug. 18, 1928, p. 309; and the comprehensive work of C. L. Fortescue and J. J. Torok, the general results of which are included in the paper by J. J. Torok on *Surge Characteristics of Insulators and Gaps* published in abridged form in JOURNAL of the A. I. E. E., April 1930, p. 276.

This latter paper, giving volt—time curves for certain types and amounts of insulation, is of particular value as the data are in the form believed to be most useful for the purposes of insulation coordination.

CONCLUSIONS

In the interest of protection to service, closer limitation of voltage stresses on apparatus, economy, and much better coordination of insulation strengths for the component parts of an electric power system is needed. To accomplish this efficiently, the development of a far more comprehensive knowledge of the characteristics of the voltages encountered, and of the insulations for their restraint, is essential. However, in the meantime, considerable improvement can be realized by a more thoughtful application of the knowledge gained to date.

The strength of the insulation system must be designed to cope with three classes of excess voltages; viz., generated over-voltages, transients from switching, faults, etc., and lightning. It is proposed that the station or terminal insulation be laid out to a basic level for supporting normal frequency and switching surges, and that in territories where lightning is not prevalent, the line insulation be established at the same level. However, where lightning occurs, the insulation level for the line should be laid out for the specific conditions encountered and it may be considerably above the level of the station. This makes it necessary that the line insulation level be coupled to the station at the line entrance in a manner to dependably discharge any lightning voltage propagated from the more highly insulated line, in excess of what can be supported by the basic insulation level of the station.

To accomplish this relation, it is proposed that the basic insulation level be established by an excess voltage spillway located at each line entrance to the station, and capable of discharging freely and repeatedly without damage. For the case where the line is insulated at a higher level, service would be improved should this spillway be equipped with a barrier to 60-cycle current without sacrificing its ability to freely discharge lightning surges.

Furthermore, for the increased security of the busses and apparatus, in keeping with their greater respective values and importance, successively higher insulation levels within the station are proposed for the bus work, apparatus bushings, and apparatus internals except in cases where, for economical and practical reasons, it may be necessary to supplement the insulation of certain types of apparatus with suitable protective devices.

For present cases, in determining quantitatively the required insulating strengths, and selecting suitable insulators and bushings from the available assortments, considerable data on impulse characteristics are already available in A. I. E. E. papers and elsewhere. However, these lack much of being complete and balanced, and as rapidly as possible must be greatly extended and coordinated by further research and calibration work.

Volt—time characteristics are considered to offer a practical method of rating insulators of various types to permit of successfully comparing and applying them in a coordinated insulation system.

The entire project is distinctly in the development and research stage, and the authors believe more progress and experience should be accomplished before recognized standardization can be undertaken to advantage of such features as lightning test waves, the characteristics of insulation and insulation levels for lines and stations.

Discussion

RATIONALIZATION OF STATION INSULATING STRUCTURES

(Fortescue)

THE EFFECT OF TRANSIENT VOLTAGES AND DIELECTRICS—IV

(Peek, Jr.)

RATIONALIZATION OF TRANSMISSION INSULATION STRENGTH—II

(Sporn)

RECOMMENDATIONS ON BALANCING TRANSFORMER AND LINE INSULATIONS

(Montsinger and Dann)

COORDINATION OF INSULATION AS A DESIGN PROBLEM

(Floyd)

STANDARDS OF INSULATION AND PROTECTION FOR TRANSFORMERS

(Johnson and Bundy)

ESSENTIAL FACTORS IN THE COORDINATION OF LINE, STATION AND APPARATUS INSULATION

(Silver and Melvin)

A. O. Austin: In the standardization of an impulse wave it would seem that there are two conditions of wave form that should receive attention. For the transmission system where flashovers mean interruptions the wave with a long tail or slow rate of decay gives the best information for judging the value of line insulation. This is particularly true for station insulation.

However, in order to simulate the condition of a chopped wave in connection with the comparative performance of arresters, voltage limiting gaps, and composite insulation assemblies, a short tail wave or one with a very high crest should also be used. Even here the wave with steep front and long tail, but with a high crest may be preferable as results comparable to the short wave will be obtained and in addition the relative performance with the long tail wave may be readily determined without changing the wave. This requires comparative tests or oscillograms. Where the short wave only is used for the same work, crest values may be obtained but there is a question as to what the performance would be under less favorable conditions.

Other factors besides wave form should be considered in standardizing lightning sparkover tests. For example, tests in the Barberton laboratory show that gap resistances (as affected by the number and length of intermediate gaps), impedances in the impulse circuit, and the capacitance of test leads are very important factors. Where the gap resistance or impedance together with leads of small capacitance come into play the sparkover of the insulator may be arrested, so that complete breakdown does not take place. In fact oscillograms show that an insulator may start to fail and then recover under these conditions only to sparkover later. Voltage measurements secured under these conditions would be very confusing.

While standardization should be very beneficial it is necessary to consider a number of factors in the test circuits before the results of different laboratories can be compared on a numerical basis. Ignoring these will lead to misinformation in the same way that the use of the chopped wave or the very short wave has for line insulation study. At this stage of the art it should be possible to cover a wide range of waves, each particular type being chosen to conform with characteristics of the insulation and service conditions.

As temperature, pressure, humidity, polarity, wind, and the electrostatic field of the test set-up, are other factors in addition to the wave form, it would seem that very close agreements of tests made even in the same laboratory may vary materially from time to time. For this reason comparable parallel tests are to be preferred, together with methods which permit as short a period of time as possible between tests.

Balancing the insulation of line, station and apparatus has always received much attention on some transmission systems. While at first glance it might appear that a chaotic situation exists in present practise, it is well to look first at several factors other than the relative impulse strength of the different elements. For example it has been known for some time that the time lag for solid and liquid insulation is usually much greater than for air. This had been made use of on many systems in order to reduce the interruptions from flashovers.

Although theoretically possible, the difficulty of balancing insulating members within 10 or 15 per cent is greater than it seems. Insulator strings and bus insulators are usually of such size that an allowance for depreciation of 10 to 20 per cent is made. This combined with the allowance for smoke and dirt will give a high insulation level, possibly well over 50 per cent of that required when the insulators are clean and new. It is a recognition of these factors that has led to the apparent lack of balance in many cases.

A slight change in a transformer design may greatly increase its ability to withstand transients. It would therefore seem that the goal should be to provide ample insulation in line and station as the best results can be obtained by strengthening the weak rather than weakening the strong. A voltage limiting device such as a fused gap or arrester can be used to protect the weak in the meantime. If line and bus insulation is limited it may not be possible to increase it later.

Among other factors which have been given careful consideration is the absorbing capacitance of the station, the small probability of a direct stroke in the vicinity of the station, and the ease of protection against direct stroke for the station.

The desire to limit the voltage on station and equipment has been given much attention in the past and it is to be hoped that the present attention given to the problem will result in material improvement both as to performance and cost. However, limiting the voltage by an arc which will cause an interruption, is hardly the answer desired, although it may be a valuable method for the time being.

S. Murray Jones: Fig. 8 of Mr. Fortescue's paper indicates that it is desirable to reduce transmission line insulation gradually, starting some distance away from stations. Although this practise has been used by some operating companies, it is, in our opinion, inviting more trouble rather than reducing it. In case of either a direct or an induced stroke, it is always desirable to have the maximum possible insulation. Therefore, it would seem desirable to maintain the line insulation at a uniform level up to the station, using either lightning arresters or voltage limiting gaps, or both, to protect the station apparatus.

Mr. Sporn, in his paper, states that the insulator manufacturers are apparently not in agreement on the 60 cycle flashover values given out for substantially the same type and design of units, to say nothing of the values given for impulse flashovers. The differences in impulse flashover values are obvious to most of us, but there should be no dissimilarity in the 60 cycle values. These differences which occur may be explained by variations in wave form or differences in temperature and humidity at which the insulators have been tested, or both. Mr. Austin has always endeavored to take these factors into consideration in figures which have been given out from our Barberton Laboratory. In fact, he has been using humidity correction factors for over 15 years. As is well known, insulator strings have characteristics when tested under different conditions of humidity, similar to that of the needle gap and it is for this reason that Mr. Austin has preferred to use the needle gap as a means of calibration for determining 60 cycle insulator sparkover voltages.

It would certainly be desirable at the present time to standardize on impulse test waves if such standardization would result in comparable figures being obtained from the different

laboratories for tests on the same types of insulation. We do not believe that standardizing on test waves would accomplish the desired purpose since, in our opinion, several other and perhaps more important factors must be included in the standardization.

The method of potentiometer coupling for determining impulse wave shapes is perhaps the most important factor to which more study must be given in an attempt to obtain a true oscillogram of the phenomena occurring at the test piece. Other factors which must be considered and included in any standardization of impulse testing are, polarity of the test wave, the method of mounting the test piece, the length and size of the test leads, the location of the potentiometer and cathode ray oscillograph, and the temperature and humidity at which the tests are taken. There may also be other important factors which must be taken into consideration before comparable results can be procured from the different testing laboratories from tests obtained on similar apparatus. Until the majority of these factors can be included in any insulator impulse test standards, we are of the opinion that it will be preferable not to attempt to standardize on wave shapes.

Effect of Shape of the Voltage Wave on the Distribution of Dielectric Stresses Within Winding

K. K. Palueff: Since the principle of coordination suggests that the transformer should be protected by gaps without a series resistance, it is of importance to understand the effect of a short ("chopped") wave on the distribution of dielectric stress within an ordinary transformer winding.

The relations between the shape of the incident wave and the corresponding stresses within the transformer winding were established rather completely in the papers presented by the author during the last year and a half. For this reason, the present discussion will be limited to the conclusions arrived at in these papers.

The entire insulation structure of a transformer winding can be divided into three categories: turn insulation, coil insulation, and major insulation, *i. e.*, insulation between a given winding and ground and other windings. All these categories are equally vital.

The following can be stated, as general laws:

1. The closer the two elements of a given winding, the higher is the frequency of oscillation capable of producing equally dangerous dielectric stress.

2. Free transformer oscillation consists of some eleven harmonics.

3. To produce a free oscillation of not less than one-half of the amplitude that would be produced by a long wave with rectangular front, of the frequency of any of these harmonics, the front or tail of the incident wave must not be longer than about 50 per cent of the period of the harmonics.

4. However, even if the front or the tail of the wave is sufficiently steep, to allow the amplitude of this oscillation to reach at least one-half of the amplitude that would be produced by a long wave with rectangular front, the length of the wave must be not less than a quarter of the period of the harmonic.

5. The oscillation at the frequency of any given harmonic (and of all higher harmonics), cannot be produced by a wave having both front and tail longer than the period of the harmonic, regardless of the length of the wave.

6. If the length of the wave with steep front and tail is equal to an odd number of half-periods of a given harmonic, the amplitude of this harmonic will be twice that produced by a long wave with the same front but with a slanted tail.

Taking as a standard for comparison, stresses created in a winding by an extremely long wave with rectangular front, the following conclusions can be arrived at from the above:

a. For turn insulation the waves with "exceedingly steep" front or tail (from, say, 0.25 to 4 microseconds, depending on transformer constants) are the most dangerous. Depending on the length of the wave, the stresses may be doubled if both the front and the tail of the wave are "exceedingly steep."

b. For the coil to coil insulation, the waves with either *exceedingly steep* or *very steep* (some 10 microseconds), front or tail, are the most dangerous. Depending on the length of the wave, the stress may be practically doubled, if both the front and the tail of the wave are sufficiently steep.

c. For the major insulation the waves having the front or tail *exceedingly steep* or *very steep* or just *steep* (not much longer than 50 microseconds) are the most dangerous. Depending on the length of the wave, the stresses in some parts of major insulation may be materially increased, if both the front and the tail of the wave are sufficiently steep.

d. An incident wave with both front and tail not shorter than the period of the fundamental harmonic of the transformer will produce a practically uniform voltage distribution throughout the winding during the entire transient, regardless of the length of the wave.

e. Up to the present, no protective devices have been developed which would limit the voltage of the incoming wave to an absolutely negligible value. Therefore, an ideal protective device should be considered one which lowers the crest of the incident wave to a safe value and also modifies the shape of the wave so that the lengths of its front and of its tail become not shorter than the period of the fundamental neutral frequency of the apparatus to be protected.

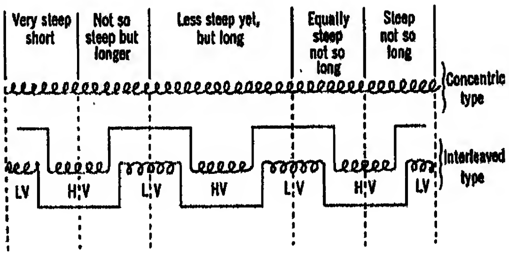

Fig. 1—Zones of High Voltage to Ground Produced in Concentric and Interleaved Windings by Lightning Waves of Various Shapes

Minimum requirements for steepness and length of the waves

f. A device that would modify the shape of the incident wave as just described, but would not reduce its crest value, would materially relieve stresses between turns and coils, but would allow the greater part of the major insulation to be over-stressed.

g. A device that would reduce appreciably the amplitude of the crest of the wave but would not properly modify its shape, would correspondingly relieve the stress on major insulation, but stresses on coil and turn insulation would not be reduced in the same proportion.

A gap without resistance in series, chops the incoming wave very abruptly. Thus, as a rule, short waves with steep front and tail are allowed to be impressed on the transformer. These waves, under circumstances mentioned above, may produce practically the same stresses between coils and particularly between turns, as waves of the same front, but with slanted tail, and with the crest twice as high.

All this applies to all ordinary transformers, (or any other inductive apparatus) of core and shell types.

In the non-resonating transformers, the stresses in turn, coil and major insulations are uniformly distributed for any shape of incident wave.

All the above emphasizes the necessity of coordination of line and transformer insulations.

To permit such a coordination, it is essential to have data on impulse volt-time characteristics of bushings, suspension insulators, pedestal insulators, etc. To permit the drawing of a volt-time curve with engineering accuracy, three arcover test

points appeared to be sufficient: one obtained with very steep and short wave, another with a wave not so steep, but much longer, (say, 30-50 microseconds) and a third with 60 cycles.

It is obvious that it would be far more desirable if different experimenters agreed on exact shape of the preferred two impulse waves. This would give a common ground for comparison of various insulating members of transmission systems.

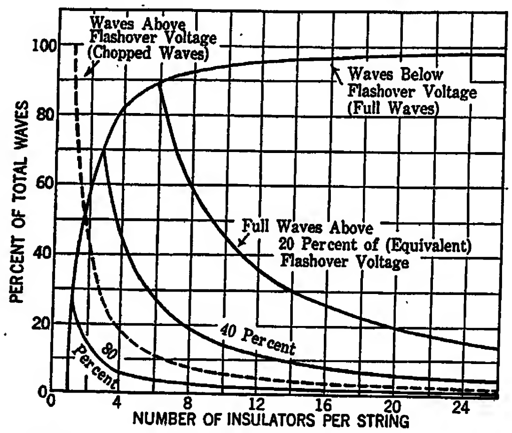

Fig. 2—Relation Between Number and Amplitude of Lightning Waves on Transmission Lines

All waves below flashover voltage of one insulator have been neglected

The Relation Between Line Insulations and Number of Arcovers

From statistical data it appears that, for a given height of conductor, its length and the number of storms per year, the number of flashovers is inversely proportional to the number of insulators, *i. e.*, $f = \dfrac{k}{n}$ or $f\,n = k$ where

f —number of flashovers per year
n —number of insulators
k —constant depending on the length of lines, the height of conductor, the number of storms per year and the number of ground wires

For 100 miles of line, 40 storms per year, one ground wire and 40 ft. height of the conductor: $K = 46$.

For any conductor with one ground wire, the relation seems to satisfy the following formula:

$$f = A\,\frac{h^2}{n}\,S\,l\,10^{-6}$$

where
f —number of flashovers per year
h —height of conductor in feet
l —length of the transmission line
A—constant (7.2 for one ground wire, 6.5 for two ground wires)
S—number of storms per year
n—number of insulators (5¾ in.)

On account of great varieties in lightning characteristics of different transmission systems, it cannot be expected that an accurate general law could be developed. Therefore, the above formula should not be looked upon as an exact law, but rather as an approximate expression of the tendency due to the various factors mentioned.

I applied the above formula to data given for a 220-kv. system by Mr. Floyd in his present paper, and found $f = 1.48$ for 15.7 of 5¾ in. insulators (equivalent to (18) 5 in. insulators). The service record gives 1.75.

I could not check the formula against Mr. Floyd's data on the 110-kv. system, as the length of individual lines is not given and no mention is made of whether the hardware on wood pole lines was grounded or insulated.

If the above formula is at all correct, then the lightning waves that appear on lines with different numbers of insulators can be segregated as shown on Fig. 2.

Service Experience with Coordination of Insulation

Since coordination of line and transformer insulation has already been put in practise by a number of operating companies, it is of interest to review some of the results.

In 1926 a 220-kv. transformer failed. The transformer was built for 346 kv., (2.73) induced voltage test with major insulation not graded, with coil and turn insulation as in a fully insulated transformer. The line insulation consisted of disks with 60 cycle arcover of 725 kv. The proposed rule of coordination in such a case would require the transformer to be tested at 461 kv. The cause of the failure is therefore obvious. It had been predicted, but in those days very few believed in the possibility of 1,800,000 volts on 220-kv. lines.

After the transformers were repaired, the line insulation near the station was reduced to correspond to transformer insulation. Since then the transformers have been examined at regular intervals and no sign of damage was found, in spite of the fact that a great many lightning arcovers have been recorded near the stations.

Mr. Floyd, in his present paper, discusses his experience with coordinated insulation on his 220-kv. system. He states that the transformers were of interleaved design with high voltage winding consisting of four groups with major insulation graded on the basis of 2.73 times normal test (346 kv.), but with line group insulated for 440 kv. This gives the following strength for various groups: line 440 kv., second 260 kv., third 173 kv. and fourth or ground 86 kv.

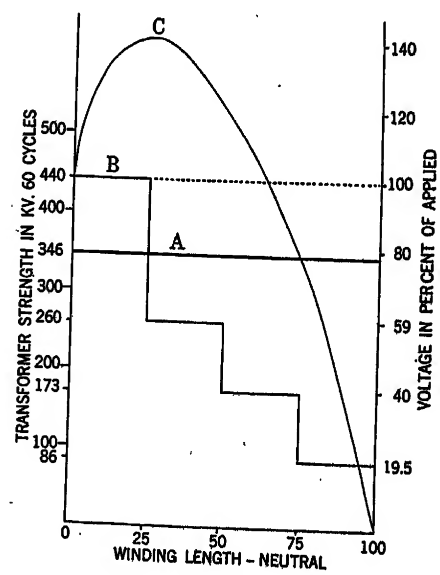

Fig. 3

A—Major Insulation of Transformer Which Failed in 1926
B—Major Insulation of Mr. Floyd's Transformer
C—Maximum Voltage to Ground that Could be Produced in Transformer B by Non-Oscillatory Single Lightning Wave

Furthermore, it is stated that line insulation for two miles next to the station had four ground wires and a 60-cycle arcover of 665 kv., which corresponds to a 422-kv. transformer test (Fig. 3 illustrates the relation between line and transformer insulation for the 220-kv. transformers mentioned).

In spite of the fact that line insulation was some 5 per cent lower than the rule of coordination requires, the transformer failed during lightning.

The study of the phenomenon indicates that, on the one hand, the grading of major insulation is not justified by the distribution of voltage throughout the winding caused by a lightning wave (Curve *C*, Fig. 3), on the other hand, to make reduced line insulation protect the station, the tower footing resistance must not be of excessive value. I should appreciate it, if Mr. Floyd would tell us just how high the tower footing resistance of the line near the station is, and whether, with his knowledge of all the details of the system characteristics, he could suggest some other reasons that made the coordination of insulation ineffective as a means of protection.

J. H. Cox: Mr. Sporn has discussed to considerable length the need for rationalization of transmission system insulation in order to effect greater reliability of service and has pointed out some desirable methods by which this scheme might be advanced. He further states that the situation appears somewhat chaotic at the present time but I must disagree with his statement that very little has been accomplished.

There can be no question but that great strides have been made in the past few years regarding the nature of lightning and the impulse characteristics of insulation, and that the situation is a great deal more clear now than in the past. For instance, at the present time fairly complete and accurate impulse ratio time lag curves for porcelain line insulation and air gaps exist along with much data regarding the nature of lightning impulses to which lines are subjected. With these data, line insulation and air gaps can now be intelligently applied on a rational basis.

Mr. Sporn has put up a strong plea for the adoption of a standard impulse wave for testing purposes. Although, since Mr. Sporn's paper was written the situation has been considerably altered, the paper is part of the permanent record and I would like to give an outline, as I see it, of the opinion of what Mr. Sporn has called, the minority.

In general there is no question but that standards should not be adopted until definite lines have been established with considerable accuracy. It is also impossible at the present time to define with any degree of accuracy the impulse characteristics of fibrous and composite insulation. An excellent example of the prior need for accurate definition is the suspension insulator. It has long been known that the impulse characteristic of any insulation is a function of voltage and time. Up until two or three years ago practically nothing was known about the quantitative values of these factors. At the present time complete curves have been determined for the impulse characteristics of porcelain insulation, so this is now on a definite basis. Had a standard wave or series of waves been adopted prior to the actual determination of the curves it would have meant nothing and might have been misleading in a serious degree. At the present time, since the curves have been determined such standard waves are not necessary.

Transformer and other more complicated insulating structures are only now in the process of being studied. The distribution of impulse voltage throughout transformers has been determined, but the impulse strength of the insulating members is still practically unknown. A great amount of work remains to be done on this problem and until this is done it is wasted effort to attempt to define these characteristics on the basis of standard waves misleading ourselves thereby into thinking that something is being defined which actually cannot be explained at the present time.

Mr. Sporn admits that any wave adopted at the present time would necessarily be a tentative standard requiring revision from time to time. Such a procedure would greatly delay the program of investigating the fundamentals since it would seriously handicap the available laboratories. For instance, after the adoption of a standard, work in the laboratories would for a time be confined to the determination of the characteristics of various insulating members in connection with the particular waves chosen. Subsequently a similar amount of work would be required each time the standards changed. It is obvious that with the available equipment now being used full time to determine the fundamentals of the problem, this determination would be handicapped.

Mr. Sporn's argument for a standard wave seems to me particularly inconsistent. In the early part of his paper he discussed the efforts of the Transformer Committee to formulate a standard method of coordinating station apparatus and gives some strong arguments against such standardization before the necessary factors are determined. Immediately following this argument he puts up a plea for standardization of test waves which so far as I can see present the same arguments. To quote from an article by Mr. Sporn which appeared in a recent issue of the *Electrical World*:

> "There have appeared, it is true, tendencies, particularly among manufacturers, to codify some of the changes in practices in this regard, but fortunately this tendency has been averted so that the entire problem is free to continue and develop itself along natural lines."

It is realized that the need for definition is great and that the time may be long before the necessary data are obtained but the facts of the case should be looked at squarely. The adoption of a standard wave at the present time would merely be the expression of the desire to fill a need rather than the accomplishment of any real results. As it is the work is progressing in an orderly fashion towards the rational solution and the real need is for greater support of the test program. The attempt to formulate definitions and standards at the present time is a side stepping of the actual problem.

To summarize, as I see it, the following points outline the objections to the adoption of standard impulse waves:

1. In general it is unsound practise to standardize on a test where this test must be based on inadequate and unproved data and there is an element of danger in forming a standard which is admittedly tentative and will require changing in the near future.

2. Even though tentative, such a standard is misleading and creates a false sense of security since one is inclined to believe that apparatus tested by an A. I. E. E. standard is adequately tested and representative of what the apparatus should withstand in practise.

3. The particular incentive in the present case for setting up a standard test seems to be to provide a comparison between different makes of apparatus, but a standard of comparison which is not based on a sound foundation may be unjust and lead to indications which are the reverse from facts.

4. After a standard has been set up competition forces a manufacturer to build apparatus to meet a standard test and tends to make him overlook the factor of service requirements which has been the predominant factor in the previous design practise.

5. In general the premature adoption of a standard tends to relax and divert efforts, and to postpone the ultimate final solution.

None of this should be interpreted as an objection to the selection of a couple of preferred waves, say a short wave and a long wave, to be used in the determination of a couple of points on the volt-time curve of such insulation for which the volt-time curves have been determined, but they should not be adopted as standards in the present state of the act.

I have one comment on Mr. Peek's paper. Mr. Peek admits that the use of the cathode-ray oscillograph in impulse tests yields more accurate and complete results but he makes a plea for the greater use of the sphere gap on the grounds that it is more convenient and permits more rapid testing, and is good enough for many purposes. It has been our experience that with up-to-date equipment and a high grade of personnel, tests with the more adequate oscillograph can actually be made as rapidly as with the sphere gap.

With the oscillograph each shot tells its story while with the sphere gap it takes a number of shots to obtain a setting. The difference in testing time about equals the time of analysis of the films. This being the case I see no reason for being satisfied with anything less than the best possible records.

M. M. Samuels: At the Northeastern District No. 1 Meeting at New Haven, May 9-12, 1928, Mr. Philip Sporn presented a paper on *Rationalization of Transmission System Insulation Strength.* To the best of my knowledge that paper was the first systematic presentation of the various problems involved. Had that paper been used by others as a guide for further study and discussion, we would be much closer to the solution of the problem than we are today.

Many papers have since been presented and a great deal of discussion has taken place, but most of the discussions not only did not result in definite answers, but they did not even bring out more definite questions than those which were raised in Mr. Sporn's first paper. Even the numerous papers presented here do not indicate any logical subdivision of definite questions. To my mind the uncertainty is principally caused not so much by the inability to answer the questions, but in the confusion of the questions themselves. That a question correctly stated is already partly answered is still an acknowledged fact. Before dividing up the various problems into definite individual questions, it would seem that three *groups* of questions can now be crystallized from the various discussions:

Group A. Shall one part of a system have lower insulation than another part of the same system, and if so what part and how much lower?

B. What shall the insulation rating of each part be?

C. What definite commercial test method shall be used to determine whether or not a piece of equipment has the specified insulation value?

While it is quite proper to study groups *B* and *C*, it is at once obvious that no definite answers can be obtained for them until the questions of group *A* have been disposed of. On the other hand, as was brought out in the paper by Messrs. Johnson and Dann and also indicated in Mr. Sporn's paper, while some may say that the questions of group *A* refer to operation and are not a fit subject for the Institute, it is true that since *B* and *C* are matters of standardization and are precisely within the scope of the Institute, and since they cannot be answered without disposing of *A*, group *A* thus also falls within the range of Institute discussion.

In an article which I prepared for the *Electrical World* before I knew that these various papers would be presented, and which was published in the issue of June 14th of that paper, I attempted to crystallize definite *sub-questions for Group A*, which I repeat here:

1. What shall be the flashover value of transformer bushings in relation to the insulation of transmission lines which are connected to the same bus?

2. What shall be the relation of the insulation of the transformer itself to that of its bushing?

3. What shall be the insulation value of a breaker bushing in relation to that of the transformer bushing?

4. What shall be the insulation value of an insulator on a bus to that of the bushings on transformers and breakers?

5. What relation shall there be between the insulation value of an insulator on a disconnect or a branch in relation to that of the bus or the bushings?

6. What part shall be assigned to the lightning arrester in this discussion?

7. When shall the line insulation close to a station be made lower than the line insulation on the rest of the line?

I also took courage and attempted to answer these questions in my own way, and also to briefly summarize these answers: My answer to No. 1 agrees with the recommendations of Messrs. Johnson and Dann, that it would be hopeless to establish any relationship between transmission line insulation and stations insulation.

To No. 2 it is my opinion that operating companies will continue to insist that transformers be so designed that the bushing flashover, before the transformer insulation fails. To Nos. 3, 4, and 5 I recommend that the insulation values for all bushings and insulators of the same voltage be standardized to be practically the same, and my answer to No. 6 is that the lightning arrester should be considered a reliable protection, and that an arrester be used for each large transformer. As regards No. 7, it is my opinion that the idea of reducing the insulation of the line close to a station is based on a very pessimistic conception of the arrester. I have more faith in arresters, and believe that the very vigorous work done on lightning investigation by Mr. Sporn and others will bring out even more reliable arresters. I do not consider my answers as anything more than suggestions, but I beg to lay great stress on the proper subdivision of the questions and to submit it for the consideration of the Committee to canvass the questions in some such form, perhaps working up an even more elaborate subdivision for group *A* and a similar subdivision for groups *B* and *C*.

But most important of all I want to emphasize the fact that the questions of Group *A* are questions of *relativity only*, and have nothing whatever to do with definite insulation ratings, types of insulators or bushings, testing methods or any particular voltage range. They are practical questions, and a canvass of practical men should bring definite answers to them.

H. L. Wallau: The papers presented indicate a general agreement among all authors that coordination is not only desirable but necessary. No one suggests a maximum insulation limit for the line, per se, provided that suitable means for reducing this limit, if necessary, are furnished at points where equipment might be jeoparidzed by incoming transients of a magnitude in excess of the value which the equipment installed could safely withstand.

With regard to transformer windings, the Transformer Subcommittee takes the stand that their impulse ratio "is fairly constant for a given wave" and by inference is fairly constant for all waves. Sporn categorically challenges this statement and its inferences and also the Subcommittee's similar statement with reference to insulator strings. Fortescue (Fig. 7) shows large differences in flash-over values of insulator strings tested by General Electric and Westinghouse engineers with waves which are presumably similar.

For a ten-unit string, Peek's 20 microsecond wave gives a flash-over of about 1350 kv. while the Trafford 20 microsecond wave gives about 70 per cent of this. Even the 60 cycle crest data for this type string differs, the Trafford tests giving a value 100 kv. above the Pittsfield tests.

In the face of these inconsistencies, Sporn's proposal to measure impulse strength by means of impulse voltages cannot seem but entirely rational and his proposal to standardize these waves, in close agreement with our present knowledge of natural lightning waves, merits careful consideration.

The Transformer Subcommittee's proposal embodies experience to date and attempts to express that experience by means of a general statement that the transformers shall be designed for impulse strengths in excess of those corresponding to a series of insulator strings, and this strength is expressed in terms of 60 cycle r. m. s. voltages. Whether this excess strength is to be 1/10 per cent or 1000 per cent is not specified, and the foot-note blandly informs us that it could not be proven in any event.

Why cumber Standard No. 13 with this proposal? Is it not wiser for the manufacturers to continue to build transformers as they are and for operators to put into effect the recommendations contained in Part II of the proposal, meanwhile both groups trying to reach a sensible agreement as to the number and characteristics of impulse waves to be standardized upon, the number of impulses from each standardized wave to which

a transformer should be subjected and the value of crest voltage for each type of wave in terms of the circuit voltage on which the transformer is to be operated?

Before these criteria can be determined (after the standard waves have been agreed upon), it will take considerable test data to determine the safe limits to be set up, but we will be progressing in the right direction and knowledge will gradually eliminate guesswork.

W. W. Lewis: In connection with the discussion of a preferred test wave or waves, it has been suggested that such wave should have some relation to the waves observed on transmission systems which were caused by natural lightning. For this reason an investigation was made by Mr. W. B. Jordan under

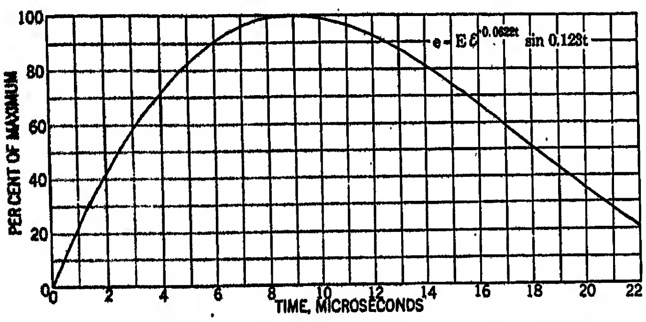

Fig. 4—Typical Oscillatory Ligthning Wave

Based on 15 oscillograms

the direction of the writer using as a basis all of the data presented at the lightning symposium given at the winter convention of the A. I. E. E. in January 1930 in the papers by Messrs. Cox and Beck, George and Eaton, Sporn and Lloyd, and Smeloff and Price.

The waves were divided in two classes, oscillatory and uni-

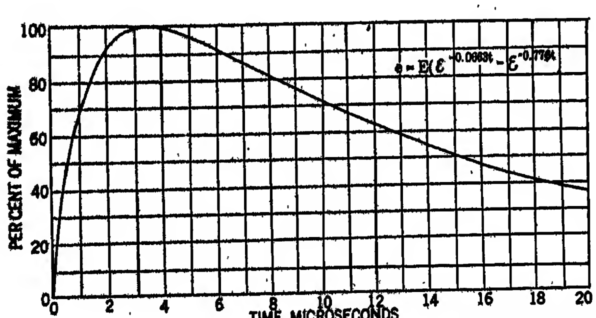

Fig. 5—Typical Unidirectional Lightning Wave

Based on 33 oscillograms

directional. It was assumed that these two classes could be represented by the type equations

$$e = E\,\epsilon^{-kt} \sin p\,t \qquad \text{Oscillatory}$$

and $$e = E\,(\epsilon^{-\alpha t} - \epsilon^{-\beta t}) \qquad \text{Unidirectional}$$

The constants k, p, α and β could be determined from the time to reach maximum, t_m, and the time to fall to 50 per cent of maximum on the tail of the wave, t_1. Both of these times are given in the data in the papers.

For a ratio of t_1 to t_m less than 8/3 and greater than 5/3, the wave was oscillatory and for a ratio greater than 8/3 the wave was unidirectional. For a ratio less than 5/3 the formulas did not apply.

Certain of the waves given were rejected on account of insufficient data or being outside the limits of the formula, and finally there remained 15 waves of the oscillatory type and 33 waves of the unidirectional type. The constants were calculated for each wave and the logarithmic mean taken for each type of wave. These mean values were substituted in the original equations to give the average wave of each type. The final equations of the mean waves were as follows:

$$e = E\,\epsilon^{-0.0622t} \sin 0.123\,t \qquad \text{Oscillatory}$$

and $$e = E\,(\epsilon^{-0.0663t} - \epsilon^{-0.776t}) \qquad \text{Unidirectional}$$

where t is measured in microseconds.

The mean oscillatory and unidirectional waves derived from these equations are plotted in Figs. 4 and 5.

In Mr. Austin's discussion he refers to the effect of humidity on the arc-over voltage of insulators and gaps and states that it will be seen that humidity has about the same effect upon the arcing voltage of a needle gap as it has upon the arcing voltage of an insulator. He concludes that where no correction is applied to the flashover of the insulator the needle gap will tend to give more consistent results than a sphere gap, even though the flashover of the latter was not affected by humidity.

This conclusion is based on the assumption that reliable data are available showing the effect of humidity on the flashover of a needle gap with a fixed spacing or on the voltage required to flash over gaps of varying spacings at a constant humidity. The further assumption is made that the variation of humidity for a fixed spacing follows a curve parallel to the curve of insulator flashover with varying humidity. Data as to these points are not available and accepted by the industry. The A. I. E. E. Rules do not sanction the use of a needle gap for voltages over 50 kv. The sphere gap, however, is sanctioned for voltages up to 800 kv. effective. It is generally assumed that the sphere gap flashover is not affected by humidity. It would seem better, therefore, in measuring the flashover of insulator strings which vary with humidity to use as a measuring device a gap which is not so affected and which is authorized by the A. I. E. E. Rules, rather than to use a gap which varies with humidity and other causes and which is not authorized by the A. I. E. E.

In the paper by Messrs. Silver and Melvin, a scheme of coordination is proposed in which the lightning arrester finds no place. In this scheme rather close margins are proposed between the setting of the spillway gap and the insulation of the bus, etc. The flashover of such a spillway gap may impose serious gradients on the insulation of adjacent apparatus, especially transformers. The writer is of the opinion that either the margin between the flashover of the spillway gap and station insulation must be very greatly increased or the lightning arrester must be brought into the picture. The lightning arrester will allow a higher setting of the spillway gap and at the same time prevent this gap from flashing over except on rare occasions.

Robert Treat: I desire to commend the basic idea expressed by Messrs. Johnson and Bundy that there need not and should not be too much coordination between the transmission line insulation on the one hand and the substation and transformer insulation on the other.

It seems to me that too many of the papers presented at this session either ignore the lightning arrester completely as a part of this picture or they treat it as an unreliable device which must have a very high degree of backup.

It is true that in former years lightning arresters were of somewhat questionable value owing to several factors:

1. It was impossible to determine with any degree of precision the protective value of an arrester.

2. Because of this difficulty lightning arresters were often improperly selected and applied.

3. Because the lightning arrester's value was questionable it was often relegated to a location which suited the convenience of the substation designer after he had completed the layout of his major apparatus.

4. The importance of an adequate ground has been really appreciated only recently.

For these reasons it is probable that many arresters have been installed in the past which gave little if any protection and as a natural result transformers and other apparatus presumably protected by an arrester, have failed. These failures have provided those who question the value of an arrester with data to support their position.

Within the last few years this situation has seen a decided change. With the advent of the cathode ray oscillograph and the lightning generator as practical tools for testing, the performance of a lightning arrester can be checked and predicted with a high degree of precision. Data are now available for the proper selection, application, location and grounding of lightning arresters in order to permit them to afford maximum protection to apparatus. Lightning arresters are now commercially available which afford a high degree of protection.

No matter how much coordinating may be done between line, substation, bushing, and transformer insulation it is perfectly clear that unless the entire insulation level is placed above the strength necessary to resist the maximum voltages which can be encountered, insulation breakdowns are to be expected. In the face of the present efforts of power companies to give better and better service, it is important in most cases that insulation breakdowns should not permit dynamic current to follow. It becomes necessary, therefore, either to have a very high insulation level throughout the whole system, or to provide spillways which do not permit dynamic current to follow the lighting current. There are relatively few devices which fulfill this condition. One of these is the gap in series with a fuse. This device, however, is not entirely satisfactory from all standpoints because once it has operated, the protection is destroyed unless a multiplicity of devices are put in parallel or some mechanism is used such as the Nicholson arc suppressor for automatically replacing fuses after they have blown. Another such device is the lightning arrester which is especially designed to perform that function.

In much of the talk concerning coordination of insulation the spread between the maximum voltage permitted by the protective insulation on the one hand and the voltage which the transformer can stand on the other, is very small—in the order of 5 to 15 per cent—and is less than the probable uncertainties in our knowledge of what these voltages actually are. The lightning arrester on the other hand will in most cases at least limit the voltage to 50 or 60 per cent of the apparatus insulation strength, and thereby provide a margin which should be adequate even for our present lack of precision in impulse strength values.

Although these facts are generally admitted there is still some disposition to regard the lightning arrester as insufficient because it may have been disconnected for inspection or maintenance, or for various other reasons it may not be on the job when needed and, therefore, backup is necessary. It is a question whether the hazard to service from this condition is as great as some commentators appear to believe. If it is, however, there is ample precedent in other fields particularly in the oil circuit breaker field for employing more than one arrester so that if one is out of commission, others will be available to maintain the protection. In such a case the margin of 40 or 50 per cent between the voltage applied to apparatus and the voltage which it can stand would never have to be reduced to the small value of 5, 10, or 15 per cent. In this connection it may be pointed out that there are types of arresters on the market today which are not only better but less expensive than ever before.

If the lightning arrester is as unreliable a device as it seems to be regarded in certain quarters, perhaps in the interest of honesty and straight-shooting we should discontinue its manufacture as we did that of the choke coil when we had determined by test that it was of little value as a protective device. On the other hand since the same group of experimenters who studied the choke coil have shown that the lightning arrester is of definite value as a protective device it should be given the credit to which it is entitled.

F. D. Fielder and P. H. McAuley: Mr. Peek has done much work on the surge breakdown of air. He is to be commended greatly for studying the effect of various wave fronts and attempting to derive empirical formulas to conform to the results. However, in doing so, he has used some data which we are unable to check in the Trafford Laboratory using what we consider to be very rigorous methods. It is stated that it may be assumed that a given amount of energy is required to break a given gap and the equations follow from this assumption. Nevertheless, the data show considerably higher flashover voltages and impulse ratios for the short fronts with other conditions the same. For instance, in Table II of the paper, the impulse ratios for ½/20, 1½/20 and 3/20 waves progressively decrease. The same statement applies to the waves with 5 and 40 microsecond tails with different fronts. This seems to show a discrepancy between theory and data. Furthermore, it is not believed possible that one equation could express the relationships for various kinds of waves where the voltages are different functions of time for the different waves.

Mr. Peek has not stated the type of surge generator and the method of taking oscillograms. We use a modified Marx generator with a resistance potentiometer to the oscillograph. We calibrate the oscillograph independently and merely use the sphere gap as a check.

Very often these two independent methods of measurement fail to check on the first trial even at the minimum sparkover point of the insulation under test. But, in every case, it has always been possible to obtain a check within 2 per cent by smoothing out the applied voltage wave. We suspect that a very highly damped oscillation may appear at the point where the wave reaches its crest. This is of such a nature that it acts as follows:

1. It has little or no effect on breakdown in non-homogeneous fields such as insulators and needle gaps.
2. It is not transmitted by the resistance potentiometer.
3. It does produce breakdown of the sphere gap.

Hence, it must be eliminated if the sphere gap is to be used successfully. It is obvious that, by calibrating the oscillograph with the sphere gap, there is a risk of introducing considerable error. We are not criticizing the sphere gap but merely stating that we find it a possible source of error. Moreover, we have found that the above source of error increases with the steepness of the applied wave front. This may account for the discrepancies pointed out above.

We would like to ask the author on what basis the wave front time is determined from the oscillograms. In Fig. 4 of the paper the front is given as one-half microsecond, but according to classical definition, the time to crest would be over two microseconds.

In connection with the adoption of a standard wave, we feel that much remains to be done in securing fundamental data. It is perhaps to be regretted that in our early work we used the term "rectangular wave" to illustrate our methods of analyses. Actually our test wave has always been approximately 1½/40 positive, using Mr. Peek's designation. It is rectangular only by comparison with a 5 microsecond wave. But the front is short enough and the tail is long enough that, for the range of time lag values usually considered, it produces essentially the same results that a rectangular wave would be expected to give. In testing we cover the full range of the "full wave" and "overvoltage" methods to secure a complete time lag curve. As a matter of fact, it is felt that the longer the tail of the wave the better, because the most pessimistic values are thereby obtained. Furthermore, for purposes of co-ordination, data obtained in this way are all inclusive of the waves recorded on lines and not

limited in application to a certain percentage of natural lightning waves like the short or 5 microsecond wave data.

Mr. Sporn has called attention to the variations in 60 cycle flashover values given out by the various manufacturers. This situation has caused us considerable concern for some time. In the Trafford Laboratory we use a 100 cm. brass sphere gap for measurement and compare the insulators under test directly with the gap by bracketing in parallel. The voltage rises at an average rate of 11,500 volts r. m. s. per second. Another group using an aluminum gap and a higher rate of rise report lower flashover values. The same calibration curves and correction factors are used in each laboratory. Hence, it is evident that the cause of the discrepancy is not readily detected. However, steps are now under way to investigate the situation thoroughly and it is expected that, in the near future, more general agreement will be attained. In this connection, it is felt that the effect of humidity cannot be neglected and possibly is responsible for a large part of the differences. Unfortunately, this is a difficult problem to study at high voltages.

J. J. Torok: Mr. Peek, in his paper, has covered a very wide field which includes both theoretical and laboratory viewpoints. From our work, which is parallel in nature, we have arrived at somewhat different conclusions. In this early work it soon became apparent that the breakdown or sparkover was a phenomenon involving two factors, namely, voltage and time. In order to segregate these elements and find the absolute significance of each in regard to breakdown, a wave had to be chosen which would hold one or the other constant. Such a wave must of necessity be rectangular in shape. In using such a wave, its shape is not changed throughout the testing cycle, only its magnitude is varied. First a low voltage is applied and the time element determined from oscillograms. Then the voltage is raised and another measurement made. This process is continued until the characteristics of the breakdown in terms of time and voltage are found for all practical purposes. Truly an ideal method, for it fulfills all requirements. Of course, the physical and economic limitations of the laboratory equipment were such that an absolute flat topped wave could not be obtained, but the deviation is so small as to be negligible in performance. This wave was designated as the Trafford Wave.

The technique of the laboratory staff has with intensive study and requirements reached such a point that the most desirable data can be obtained with the cathode-ray oscillograph in the same period of time as was required with the sphere gap alone.

Subsequent to our work on flashover, Mr. Cox entered into a correspondence with Professor Ryan on the mathematical analysis of flashover time. Together they worked out a fairly satisfactory solution based on the laws of thermal ionization and streamer propagation. However, Mr. Cox, considered these calculations of theoretical interest but of little practical value because of the independent variables which could not be predetermined for an unknown condition.

To obtain a true prospective of the entire lightning field, we had to obtain considerable information in the field which klydonograph data did not give. The oscillograms obtained in the field were classified into two groups, first those which caused line insulation flashover and, second those which did not. The first group, because of distortion by flashover, could not be used for determination of the nature of the wave. The second group of data, however, were useful in this connection. Most of them were of 50-150 microseconds duration. This indicated that either the cloud discharge area was from 10-30 miles in extent or that the cloud discharged in 50 to 150 microseconds. It is well known from meteorological data that the discharge area is of the order of one-half to one mile in extent. The discharge being of such long duration, we found from Bewley's work as well as Mr. Peek's curves, that the maximum induced voltage cannot exceed 100 to 150 kv. on a 50-ft. line.

In further correlating our field and laboratory data with theory, we have found that any given wave shape of the second group will not cause flashover at any fixed impulse ratio but that the factor of magnitude is vitally interlinked, so that any impulse ratio ranging from one and upwards, might result. Incidentally in the work it soon became apparent that the change of wave shape on a line was caused by corona or tap off lines and that the wave upon formation was of exactly the same shape as it was later when it was in motion.

Carrying this conception to transmission lines, we are led to believe that with greater quantities of insulation and a given wave, the flashover will take place in a period of time much longer than if the insulation were reduced. This means that the impulse ratio would be much lower on a 220-kv. line than on a 110-kv. line.

C. L. Fortescue: The results of observations made during the past two years have forced Westinghouse engineers to conclude that induced surges due to lightning strokes were of no consequence on high voltage lines and that it was necessary to look to direct strokes as the cause of transmission line outages due to lightning. The first evidence of the fact that the induced surge was not an important factor arose during the lightning investigation at our Tennessee station in 1928. The lightning storms were of frequent occurrence in close proximity to the line and in spite of the fact that strokes to earth took place at distances varying from one-fourth to one mile there was no indication of any surge on the cathode ray oscillograph. The calibration of this instrument in the Tennessee test was such that any surge potential exceeding line voltage would have given a record on the photographic film. Later on in 1929 the same results were experienced in all our field stations: on the 220-kv. line of the Public Service Electric & Gas Company at Stillwater, New Jersey, our station on the Turner-Logan Line of the American Gas & Electric Company in West Virginia, and our station at Frankfort, Illinois, on the lines of the Public Service Company of Northern Illinois.

Although the scientific evidence of the observations of the past two years is quite convincing, at the same time, in order to establish the proposition that induced surges are not an important factor in producing outages on high voltage transmission lines, a theory of induced surges which will account for these observed facts seems necessary. The basis for the classic theory of induced surges is founded on the erroneous assumption that the cloud is a conductor and therefore can discharge to earth in a very short time. The fallacy of this has been exposed by a number of prominent scientists. Sir James Thompson, Sir Ernest Rutherford and others have shown that the conductivity of air depends upon the number of free electrons present. Townshend and others have shown that the sparkover in air also depends upon the number of free electrons present and it has also been shown that an ionizing agent such as ultra-violet rays will affect the apparent strength of air. A number of early investigators have shown that in an atmosphere highly saturated with water vapor when a cloud is formed the free electrons are absorbed by the particles of vapor such that their mobility is lost and thereby the conductivity of the cloud is reduced. This is also further borne out by the fact that high humidity increases the sparkover voltage of insulators and needle gaps though its effect on sphere gaps is very slight. It is therefore an established fact that the atmosphere in the interior of a cloud, far from being a conductor, is a very good insulator.

Another fact that the protagonists of the classic theory of induced strokes have lost sight of is that in order to discharge a cloud instantly the whole charge would have to be concentrated in a very small volume, and assuming that a channel had been provided from cloud to earth, this charge would have to move over this path to earth as a concentrated charge. Since it requires a concentrated charge of twenty coulombs a mile above the earth to produce a potential gradient of 50,000 volts

per ft. the actual potential of this charge concentrated in a small volume would be enormous, very many times greater than the value that a number of scientific observers have estimated as the potential of the cloud to earth. If, on the other hand, the assumption is made that the cloud is a good conductor of spherical form one mile in diameter and that this charge is distributed through this conductor (which would be physically impossible), it will require five microseconds for the more remote portions of the charge to reach the point of discharge. Therefore, a minimum limit for the complete discharge would necessarily be at least seven microseconds.

When we consider the possible rate of discharge on the basis of the actual characteristics of the cloud the rate at which this can take place seems to be comparatively slow. In the first place the mobility of the charged particles of water forming the cloud is so low that discharge cannot take place in a reasonable time through motion of these charged particles. The only way in which a volume of cloud can be discharged is by ionization within the cloud itself. This process within the atmosphere of the cloud is much slower than in ordinary air on account of the small number of free electrons present. The rate of progress of the streamers within the cloud will therefore be no greater than one-twentieth the velocity of light and probably considerably slower than this. The mechanism of discharge would be probably as follows: As the streamer to earth forms, the portion of the charge in the cloud immediately adjacent to the streamer will go into the formation of the streamer and thereby a high gradient will be set up in the portion of the cloud in the immediate neighborhood of the streamer. The streamers will therefore begin to form outward from this portion of the cloud into the body of the cloud; as they progress an increased portion of the cloud charge is tapped and carried into the streamer forming to earth. When the streamer reaches earth the gradient in the cloud is increased on account of the greater demand for current to support the ionized channel to earth so that the rate of progress of the streamers into the body of the cloud is increased. After a while a point will be reached where the further progress in the formation of streamers in the body of the cloud will not supply the amount of current necessary to sustain the lightning channel to earth and the lightning stroke will cease. Considered on this basis it will be plainly evident that to discharge a volume of the cloud a mile in diameter would require at least 100 microseconds. If this volume contained 20 coulombs the average rate of discharge would be 200,000 amperes.

A very interesting up to date treatment of the discharge from cloud to cloud and from cloud to earth is given by Dr. G. C. Simpson in his Twentieth Kelvin Lecture entitled "Lightning," delivered before the Royal Institution, April 25, 1929. For a more detailed treatment of the subject the reader is referred to this lecture. In this article Dr. Simpson makes the following statement: "A very important factor in connection with a lightning discharge is the time element. Wilson has not determined this, but we have recent measurements by Norinder and Matthias and, if we may accept the opinion that atmospherics are due to lightning discharges, we have the large mass of data collected by Watson Watt. All these determinations agree in making the average duration of a lightning discharge greater than 0.001 second. A discharge of twenty coulombs in 0.001 second gives a mean current of 20,000 amperes—a value agreeing well with the direct observations of current made by Matthias. This mean value must, however, be greatly exceeded for short periods during the course of a discharge, and we may well expect instantaneous values of the order of 100,000 amperes." I think it probable that in a very severe lightning stroke the maximum rate of discharge may reach a value of 200,000 amperes but, if according to the classic theory, a complete discharge of the cloud will take place in two microseconds, the rate of discharge would have to be of the order of 10,000,000 amperes which is obviously an impossible value and even if the upper value of five microseconds mentioned by some of the protagonists of the classic theory were true the current would have to be of the order of four million amperes. It does not seem likely that such observers as Norinder, Matthias and other scientists who have measured the value of current in the lightning discharge by various means should be so far out in the order of the measurements that they have made. Let us now consider the value of the induced surge due to a lightning stroke in the close vicinity of a long transmission line.

It will be assumed that the discharge takes place between cloud and earth and that a uniformly charged spherical volume of the cloud whose center is a height H above the line is completely discharged, the total quantity being Q. Then if the discharge takes place instantly, the potential induced on a line of height h above ground at a point x distant from the point on the line vertical below the center of the sphere may be obtained on the basis that the release of the bound charge will give rise to the same potential as that which would be induced on a similar line that was insulated from earth. We may assume that if h is small compared with H the gradient from h to earth will be uniform and vertical and the value of the gradient at x will be

$$\frac{2\,Q\,H}{(H^2+x^2)^{3/2}}.$$

The induced potential on the wire will be

$$\frac{2\,Q\,H\,h}{(H^2+x^2)^{3/2}}.$$

The discharge of the cloud over the lightning path is, however, comparatively slow. If we assume that this discharge takes place at a uniform rate i, the amount discharged during the time $d\,t$ is

$$i\,d\,t = \delta\,Q.$$

We may, therefore, take for the released potential at any point x due to the increment $d\,Q = i\,d\,t$.

$$\delta\,V = \frac{2\,i\,H\,h}{(H^2+x^2)^{3/2}}\,d\,t.$$

This increment of potential divides into a positively and negatively traveling surge expressed by

$$H\,h\left[\frac{1}{\{H^2+(x+\alpha\,t)^2\}^{3/2}}+\frac{1}{\{H^2+(x-\alpha\,t)^2\}^{3/2}}\right]i\,d\,t$$

The increment contributed to the potential of the surge at the point x at time T due to the increment of potential released at time $t < T$ is given by

$$H\,h\left[\frac{1}{[H^2+\{(x+\alpha\,T)-\alpha\,t\}^2]^{3/2}}+\frac{1}{[H^2+\{(x-\alpha\,T)+\alpha\,t\}^2]^{3/2}}\right]i\,d\,t$$

The total potential of the surge at time T is therefore

$$H\,h\int_0^T\left[\frac{1}{[H^2+\{(x+\alpha\,T)-\alpha\,t\}^2]^{3/2}}+\frac{1}{[H^2+\{(x-\alpha\,T)+\alpha\,t\}^2]^{3/2}}\right]i\,d\,t$$

$$H^2+\{(x+\alpha\;T)-\alpha\;t\}^2=H^2+(x+\alpha\;T)^2-2\;\alpha(x+\alpha\;T)t+\alpha^2\;t^2$$
$$H^2+\{(x-\alpha\;T)+\alpha\;t\}^2=H^2+(x-\alpha\;T)^2+2\;\alpha(x-\alpha\;T)t+\alpha^2\;t^2$$

The integrals of the two terms in the bracket are

$$\text{First Term}\left[\frac{\alpha^2+-\alpha\,(x+\alpha\,T)}{\alpha^2\,H^2\,\sqrt{H^2+\{(x+\alpha\,T)-\alpha\,t\}^2}}\right]_0^T$$

$$\text{Second Term}\left[\frac{\alpha^2\,t+\alpha\,(x-\alpha\,T)^2}{\alpha^2\,H^2\,\sqrt{H^2+\{(x-\alpha\,T)+\alpha\,t\}^2}}\right]_0^T$$

Taking the limits we have

$$\text{First Term} = \frac{x + \alpha T}{\alpha H^2 \sqrt{H^2 + (x + \alpha T)^2}} - \frac{x}{\alpha H^2 \sqrt{H^2 + x^2}}$$

$$\text{Second Term} = \frac{x}{\alpha H^2 \sqrt{H^2 + x^2}} - \frac{(x - \alpha T)}{\alpha H^2 \sqrt{H^2 + (x - \alpha T)^2}}$$

The complete solution is therefore

$$\frac{i\,h}{\alpha H} \left\{ \frac{x + \alpha T}{\sqrt{H^2 + (x + \alpha T)^2}} - \frac{x - \alpha T}{\sqrt{H^2 + (x - \alpha T)^2}} \right\}$$

For $x = 0$ we have potential at end of time T.

$$V_T = \frac{2\,i\,T\,h}{H \sqrt{H^2 + \alpha^2 T^2}}$$

$$\frac{d\,V_T}{d\,t} = \frac{2\,i\,h\,H^2}{H\,(H^2 + \alpha^2 T^2) \sqrt{H^2 + \alpha^2 T^2}}$$

The value of V_T will reach its maximum when

$$\frac{d\,V_T}{d\,t} = 0.$$

This gives

$$H^2 + \alpha^2 T^2 = \infty$$

or

$$\alpha T = \infty \text{ and } Q = 20 \text{ coulombs.}$$

This simply states that assuming a constant rate of discharge V_T will keep on increasing so long as the discharge lasts and will cease to increase when the discharge stops.

If $i = 200{,}000$ then the maximum will be reached in 100 microseconds. We infer that the important data is the average rate of discharge of the cloud during the first few microseconds since the rate of building up is most rapid during this time. We will not be justified in ignoring the discharge rate during the formation of the streamer from cloud to earth, as the space charge formed along the discharge channel probably accounts for a very substantial part of the total discharge from the cloud, but the results obtained on the assumption that the cloud discharge reaches its average value instantaneously will have the advantage of being conservative.

For a discharge a distance d from the line we may substitute for H^2, $(H^2 + d^2)$ and for V_T the expression will be for the point $x = 0$

$$V_T = \frac{2\,i\,T\,h}{\sqrt{H^2 + d^2} \sqrt{H^2 + d^2 + \alpha^2 T^2}}$$

$$V_T = \frac{2\,i\,T\,h}{H \sqrt{H^2 + \alpha^2 T^2}} \times 9 \times 10^{11} \text{ volts.}$$

Where the cloud discharge is distant d from the line, the maximum value of the surge at the point $x = 0$ is

$$V_T = \frac{2\,i\,T\,h}{\sqrt{H^2 + d^2} \sqrt{H^2 + d^2 + \alpha^2 T^2}} \times 9 \times 10^{11}$$

Where the value of $H\,h\,d$ are given in centimeters and α is given in centimeters per second. To obtain V in volts when i is given in amperes the factor 9×10^{11} is included in the equations given above.

Let us now consider some numerical examples. Assume a spherical portion of a cloud which is uniformly charged and whose center is 5000 ft. above the earth to be discharged by a stroke of lightning and let the height of a line in close proximity to the discharge path be 50 ft. What will be the maximum voltage induced? Here $\frac{h}{H} = \frac{1}{100}$, and if we assume a current $= 200{,}000$ we obtain

$$V_{max.} = 120{,}000 \text{ volts.}$$

If the line is one mile from the point of discharge

$$V_{max.} = 85{,}000 \text{ volts.}$$

Thus it will be seen that the values obtained by taking into account the slow rate of discharge of the cloud, adequately explain the fact that at numerous observation stations no value of induced surge due to lightning stroke has been observed which will cause the cathode beam to move off the target of the Norinder cathode ray oscillograph when the width of this target is such as to preclude the line voltage from appearing on the film. It seems appropriate also to remark that if, as a result of the lightning stroke, surges corresponding to gradients of 50,000 volts per ft. appear on the transmission line the difference in induced effect of a stroke right adjacent to the line, and one a mile or two miles away is not very great, the former induces a value 71 per cent of the value due to the stroke in close proximity to the line and the latter 45 per cent. If, therefore, values of induced stroke corresponding to a gradient of 50,000 volts per ft. were produced, strokes one mile away would give values corresponding to a gradient of 35½ volts per ft., or two miles away a corresponding gradient of 22½ volts per ft. These values are so large that it would be impossible for a lightning storm in the neighborhood of a line to fail to give indications on the cathode ray oscillograph. In fact each thunderstorm lasting for an hour would give perhaps as many as 100 records varying in magnitude from a few hundred thousand volts up to millions of volts. This does not correspond with the results backed by observations.

To complete the argument it must be shown also that the probability of direct strokes to line rather than to earth must be such as to account for the average number of surges of magnitude higher than the above value estimated as due to induction which has been observed by cathode ray oscillographs and klydonographs. Let us consider a cloud some 2000 ft. above the level of the earth, moving over a transmission line, then if the ground wires on the transmission line are some 90 ft. above the surface of the earth we will find that if we take a 2000-ft. radius with each ground wire as center and strike an arc intersecting the surface of the cloud, these points struck from every point on the two ground wires over which the cloud is passing will bound an area of the cloud in the form of a broad band 600 ft. wide on either side of the tower. Within this band every stroke which forms will hit the tower or ground wire rather than the earth. If the cloud extends for two miles on either side of the center line of the transmission line, this band in the cloud will comprise approximately 6 per cent of the total area of the cloud. If it is assumed that the strokes originate equally from every portion of the cloud and there are an average of three strokes a minute, in one hour there will be a total of 180 strokes from cloud towards earth of which 10 or 11 will probably strike the ground wires. This proportion of direct strokes corresponds very well with the results of actual observations on transmission lines by utility engineers as well as with the results that have been obtained by means of the klydonograph and the cathode ray oscillograph.

The other evidence in support of the theory advanced is the existence of lines passing through territory where ground resistance is very low, which are practically immune from outages due to lightning. The difference in protective effect of ground wires against induced strokes when well grounded and otherwise is not sufficient to account for this immunity as compared to other lines built over territory where ground resistances are high. On the other hand, if only direct strokes are of importance, the fact of low ground resistance completely accounts for this immunity. It is hoped that the future work in connection with lightning will give us more data as to the value of the current in the lightning strokes and also in regard to the potential of such a stroke when it strikes the ground wires of a transmission line. When such data are available it should be possible to design

a transmission line in such a manner that outages due to lightning will occur very rarely.

K. B. McEachron: In discussing this paper it would be helpful if Mr. Fortescue would supply certain information in regard to Fig. 1.

1. How many insulators were used in the test?
2. What was the rating of the arrester?
3. Was the arrester for grounded or non-grounded neutral service?
4. Does the applied surge shown represent a traveling wave, or was it a laboratory representation of a traveling wave?
5. If a laboratory impulse, does the rate of current rise and crest value of the current through the arrester correspond to those which would be found on an actual transmission line?

The answer to these questions are important, as they determine the form of the arrester characteristic volt-time curve during discharge.

Under the caption, "Lightning Arresters as Protection of Line against Flashover," Mr. Fortescue explains that if arresters are used in the station, the insulation of the line for one-half mile can be graded without increasing the outage factor of that portion of the line. Mr. Fortescue's statement is based entirely upon the assumption that the wave is traveling into the graded section with such a crest voltage and wave shape that the first insulator in the graded section will not have time to flashover in the time taken for the wave to travel to the arrester and the reflected wave to travel back. This fact is shown very clearly in Fig. 8 of the paper, in which the author has shown the number of suspension units which can be protected at various distances back from the lightning arrester.

It should be pointed out that this variation in number of insulators extending back from the station was not contemplated in the method No. 3 proposed by Montsinger and Dann. These authors propose a limitation of the line insulation to earth from points within 100 circuit ft. of the terminals of the apparatus to points approximately one-half mile therefrom, the values not in excess of the flashover voltage in Table I of their paper. It is obvious, I believe, that the method proposed by Montsinger and Dann is one in which the lightning arrester at the station will be unable to give protection at points even a few hundred feet from the lightning arrester.

For direct strokes with extremely steep wave fronts and high applied voltage much in excess of the flashover of the insulator, where flashover takes place on the front of the wave, it is probable that the curve in Fig. 8 does not apply. In other words if the flashover voltage of the insulator has been reached before the wave has had an opportunity to reach the arrester and return, the arrester could not give protection. It is probably true, under severe direct stroke conditions, that the insulator in the graded section would have flashed over, even if it had been equal to the insulation out on the major portion of the line. Thus it is probable that the grading could be so arranged that the number of outages from direct strokes in the graded section would not be materially increased by this reduction of insulation. It does not seem to me that the method proposed by Montsinger and Dann entitled, "method No. 3" or the improved method suggested by Fortescue of grading the insulation represents the best practise from the standpoint of ability of lightning arresters to prevent outages where such low levels of insulation may be placed.

In attempting to protect the line insulators against flashover by the use of line arresters, it seems that the arrester could only protect the insulator nearest itself. Unlike stations where most of the waves come traveling in over the line, the highest voltage is at the point of inception and this is the point where protection is required, and if a large percentage of the flashovers are caused by direct strokes, the line arrester could not protect insulator strings a half mile distance and it is doubtful if even insulators in the next span could be so protected unless direct strokes have a certain slowness of wave front, coupled with comparatively small energy. Transmission line arresters as designed at present will not safely handle severe direct strokes. These arresters are capable of handling currents corresponding to induced charges on transmission lines but it is doubtful if it is economically possible at this time to produce an arrester which will successfully handle large currents of the order of ten, twenty, or thirty thousand amperes, as may occur in even the moderate direct stroke.

Mr. Fortescue in his analysis shows that with arresters approximately one mile apart all steep waves having crest voltages of 23 per cent above the 60 cycle flashover will cause a string in the middle of span to flashover. Assuming a 500-ft. span and using Fig. 6 of Mr. Fortescue's paper, it appears that all waves having crest values of 65 per cent above the 60 cycle flashover value and a rate of rise of front, which is fast compared to one microsecond, could cause a flashover. The conclusion is that line arresters should be close together and they will not be safe against the effects of direct strokes unless the current is rather small. Another advantage in placing arresters close together is that in many cases two arresters will be able to help a third arrester in carrying the current, so that the total current carrying capacity will be somewhat increased over that of one arrester. It seems to me that the present type of transmission line arrester should be able to successfully protect in those cases where the current flow does not exceed the values which would be obtained under induced conditions. It is felt, however, that experience should be gained with this form of protection and it does represent a means of reducing the number of outages due to lightning. In general this form of protection will be probably most efficacious in reducing the per cent of outages on low voltage lines. This comes about because of the fact that the percentage of direct strokes to induced strokes which cause flashovers is probably greater on the high voltage line.

Discussing the paper by Messrs. Montsinger and Dann: The 60-cycle strength of apparatus insulation is determined by the magnitude of the 60-cycle voltage which is a definite value for a given system. At the present time the impulse voltage is not a fixed definite value, because the system insulation varies greatly and the protective measures employed vary also. I believe the best method at present which may be used to establish an insulation level is to install a gap close to the transformer terminals and depend on the lightning arrester to prevent the gap from sparking.

In general I do not believe the use of the gap alone or in combination with a fuse, as suggested by Messrs. Johnson and Bundy is desirable unless all other means fail, because the flashover of a gap gives rise to an extremely steep tail which will cause oscillations in inductive apparatus. Of course, if this gap can be set low enough and still not interfere with service, it may be that this form of protection will result satisfactorily in some cases. However, the usual operating practise does not indicate that gaps set as small as those suggested by Messrs. Johnson and Bundy can be employed successfully on transmission systems. The ideal protection for a transformer is a device which will hold the impulse voltage to a value slightly below the 60 cycle failure voltage of the insulation for all forms of applied waves. The chopping of a wave is not the best method of protection.

There has been in recent years a very considerable change in attitude with regard to arresters for high voltage systems. This has come about largely because of the increased knowledge of arrester performance and improved design. I am confident that the arrester represents the proper solution of the problem. The use of the gap in parallel with the arrester is advantageous, because it becomes a measure of arrester performance and gives the designer of the apparatus a definite mark to which to design. This scheme should be welcomed alike by the manufacturer of the transformer and the lightning arrester, and also the

operator who uses such equipment. It furnishes a demonstration of whether or not the arrester is performing properly and also supplies to the manufacturer of the transformer a definite limit of the impulse voltage which can be applied to the equipment. In my estimation this method of establishing a reference level of insulation is much to be preferred to method No. 3 suggested by the authors, which refers to the reducing or maintaining a certain level of insulation out on the transmission line for a distance of a half mile from the station.

Mr. Floyd in his paper, suggests that the arrester be made the basis for determination of coordination. This is interesting, but I do not believe that the point has been reached where this can be done. It seems the safest procedure is to base the insulation level on the gap using increased insulation on the bushing and transformer in succession, so that the transformer winding is the strongest link in the chain. The use of the gap not only simplifies the transformer designer's problem but it also simplifies the arrester designer's problem as an arrester which protected the gap under all conditions of wave front would be an adequate arrester, providing of course that the gap was properly chosen.

I do not favor changes in insulation to the coordinated level at a point one-half mile away from the station, because in such a case the arrester is not in a good position to protect service. If such insulation levels are to be established they should be graded with the weakest insulation nearest the arrester. However, the gap method is more definite and should be of value in proving the value of the modern arrester, as well as acting as a last line of defense for direct strokes or in case the arrester for some reason is temporarily out of service.

J. F. Peters: I am in entire agreement with the authors on the importance of coordinating the insulation of the various parts that make up a substation and also in agreement with their suggestion of caution being taken in the establishment of standards for insulating practises at the present state of the fundamental data.

However, I am not in complete agreement with their suggested ultimate basis for coordination. For instance, I do not believe that it is practical to introduce as many gradations into insulation between adjacent line insulation and the bushings of the apparatus. When we consider that the flashover value of line insulators, bus supports and bushings may vary 10 per cent due to constructional variations and then attempt to establish positive margins between these various steps, the final step, that of the apparatus bushing, will involve more expense than can be justified. If the flashover of one definite point be fixed in value, say the adjacent line insulation, a relief gap or lightning arrester, and all other insulating structures including bus supports, bushings and apparatus, are made higher with a comfortable margin, a more economical and entirely satisfactory coordination will be accomplished. Also, to determine the coordination between the various parts it is not necessary to consider the complete volt-time curve between 60 cycles and short impulses. This range of course must be taken into consideration in the laboratories where the design constants for the apparatus and insulators are determined but after they have been determined for the designer it should be sufficient to use a few points, perhaps one, in carrying out the coördination.

After obtaining the fundamental data in the field and laboratories it would be unsafe to apply these data without first considering how they agree with experience. The authors suggest relative values for three of the insulation levels, 100, 110, and 115 and state that those margins should exist for all ranges of waves having impulse ratios from unity to very short waves. That would mean that the margin should apply to 60 cycle flashover values. Now if we consider the line insulation suggested in the Montsinger-Dann paper as representing normal line insulation adjacent to stations then add 10 per cent for bus supports and 5 per cent more for bushing flashovers it would be found that bushings for high voltage apparatus should be increased 25 to 30 per cent, yet experience shows that these bushings are adequate as they are now being built. Experience, after all, is the proof of adequacy of any device, whether it be machine or insulation.

It is easy to conceive that after obtaining larger amounts of fundamental data both in the field and in the laboratories that our present ideas of insulation will be considerably modified but until such data is available it is my belief that the safest and soundest way to coordinate the insulation is the method given in the paper by Messrs. Montsinger and Dann.

Edward Beck: There has been some discussion of the relative importance of direct strokes and induced surges, and of the probable severity of direct strokes. The data secured by field investigations of natural lightning disturbances seems to indicate that on high voltage lines the voltages caused by induction from discharging clouds are not sufficiently high to cause concern and that the danger to insulation lies in the direct stroke. It has in the past generally been assumed that direct strokes into circuits produced voltages and currents of such magnitudes that it was impossible to cope with them. This opinion must be revised. Undoubtedly the direct strokes which occur are of varying intensity and it is the writer's opinion that the magnitude of the currents involved are only in unusual cases of the order of the higher values which have been mentioned. This opinion is based on field observations and experience with lightning arresters distributed along high voltage transmission lines for the purpose of reducing insulator flashovers.

In the spring of 1929 the company with which the writer is associated, with the cooperation of several operating companies made installation on 66-kv. and 110-kv. transmission lines totaling about 200 arresters spaced at intervals varying from one mile to several miles on different lines. These arresters are of the new autovalve type described before the Institute in October, 1929 and January, 1930, with cross section of discharge path equal to that used in the usual types of distribution arresters. They are installed on exposed transmission lines where flashovers have been frequent. They are thus exposed to severe service because one or two sets will always be near the origin of a disturbance, and the discharge currents passed by the arresters will be a function of the lightning voltage impressed on the line. It is highly probable that direct strokes have occurred to the lines on which these arresters are installed, in fact, the writer's opinion is that there have been numerous such cases because of the fact that outside of the protective zone of the arresters, flashovers have occurred. Yet so far, only one failure of a line arrester of this type has occurred, this being due to lightning. It is to be expected that the arresters used if subjected to discharge currents in excess of 10,000 amperes for the durations expected from the oscillographic records of lightning would be destroyed. If this is so, then the experience with these autovalve arresters indicates that the transient currents involved are not usually of the tremendous values which at various times have been ascribed to them. If direct hits into the line always involve the maximum voltages and currents that have been estimated, no reliable actual measurements exist, therefore the protection of high voltage lines against flashover by distributed lightning arresters would be impractical because the arresters would be destroyed. Fortunately, in the light of our experience with distributed high voltage arresters since the spring of 1929, this does not seem to be the case.

As stated in the paper by Mr. Cox and the writer presented before the Institute last winter, direct strokes are no doubt of varying intensity and in the writer's opinion it is probably only in unusual cases that they involve very high currents in the circuits which they strike. Thus the protection of transmission lines offers possibilities which are being thoroughly investigated. We hope to publish a report covering the progress of this work in the near future.

L. V. Bewley: The impulse sparkover of a given specimen

depends upon the applied wave shape and its polarity, the ultimate d-c. sparkover value e_0; and subsidiary factors such as temperature, barometric pressure, humidity, etc. Mr. Peek has found that most impulse sparkovers follow, to a surprising degree of accuracy, the equation

$$e = e_0\left(1 + \frac{a}{\sqrt{t}}\right)$$

where

e_0 = ultimate d-c. sparkover
t = time counted from the instant that the impulse is applied
a = an empirical constant depending upon the type of gap, wave shape used, etc.

An equation of this type results from energy considerations in the case of a rectangular wave, and therefore suggests the possibility of specifying the impulse sparkover of a given gap and wave shape in terms of its rupturing energy W and its ultimate d-c. sparkover voltage e_0.

The corona energy given to the gap is

$$W = \int_{t_0}^{t} (e - e_0)^2 \, d\,t$$

or

$$\frac{W}{e_0^2} = \int_{t_0}^{t} \left(\frac{e}{e_0} - 1\right)^2 d\,t$$

where

$e = f(t)$ = applied impulse as function of time
t_0 = instant at which $e = f(t) = e_0$
t = instant of sparkover

If

$e = f(t)$ is known, then $(e - e_0)^2$ integrates as

$$W = \int_{t_0}^{t} (e - e_0)^2 \, d\,t = F(t) \Big/_{t_0}^{t} = F(t) - F(t_0)$$

Now if e_0 and W are known for the given gap and wave shape, then the instant of sparkover is determined from the equation

$$F(t) - F(t_0) = W$$

and the corresponding sparkover voltage is

$$e = f(t)$$

If $(e - e_0)^2$ integrates into a transcendental equation, or if $f(t)$ is given as a curve whose equation is unknown, then the following graphical method is applicable:

(1) Draw the curve of the applied impulse $e = f(t)$, and the e_0 line intersecting $e = f(t)$ at $t = t_0$ and $t = t_1$

(2) Construct the curve of $(e - e_0)^2$ between t_0 and t_1

(3) By trial find the area A under the $(e - e_0)^2$ curve out to a time t (where $t_0 < t < t_1$) such that $A = W$. Then t is the instant of sparkover and $e = f(t)$ is the sparkover voltage.

As examples of the application of the energy equation to different wave shapes, three cases are worked out below.

(A) Sparkover on a uniformly rising front

$e = f(t) = \alpha\, e_0\, t$ = applied impulse
$t_0 = 1/\alpha$ = value of t for which $e = e_0$
$\beta = e/e_0 = \alpha\, t$ = impulse ratio

$$\frac{W}{e_0^2} = \int_{1/\alpha}^{t} (\alpha\, t - 1)^2 \, d\,t = \frac{1}{3\,\alpha}\,(\beta^3 - 3\,\beta^2 + 3\,\beta - 1)$$

$$\beta^2 - 3\,\beta + 3 - \frac{1}{\beta} = \frac{3}{t}\;\frac{W}{e_0^2}$$

(B) Sparkover on top of a rectangular wave

$e = E$ = applied impulse
$t_0 = O$
$\beta = E/e_0$ = impulse ratio

$$\frac{W}{e_0^2} = \int_{0}^{t} (\beta - 1)^2 \, d\,t = (\beta^2 - 2\,\beta + 1)\; t \;=\; 1 + \frac{\sqrt{W/e_0^2}}{\sqrt{t}}$$

(C) Sparkover on tail of an exponential wave

$e = E\,\epsilon^{-\alpha t}$ = applied wave
$t_0 = O$
$\beta = e/e_0$ = impulse ratio

$$\frac{W}{e_0^2} = \int_{t_0}^{t} \left(\frac{E}{e_0}\,\epsilon^{-\alpha t} - 1\right)^2 d\,t$$

$$\left[\left(\frac{1 - \epsilon^{-2\alpha t}}{2}\right)\beta^2 - 2\,(1 - \epsilon^{-\alpha t})\,\beta + \alpha\, t\right]\frac{1}{\alpha}$$

$$t_1 = \frac{1}{\alpha}\log\beta = \text{time at which sparkovers cease.}$$

Curves of these equations have been plotted in the accompanying figure. They show the same type of characteristics as obtained from experimental sparkover data, but the numerical agreement is not very accurate. The most surprising point

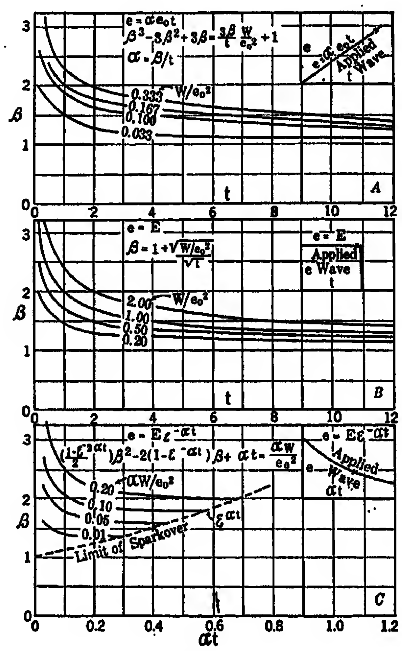

FIG. 6

brought out by a comparison of these curves with actual sparkover data is the considerable difference in the energy that it takes to break down a given gap with different types of waves.

Take, for example, the data on insulator sparkover given in Figs. 5, 7, and 17 of Mr. Peek's paper:

Fig.	Type of wave		β	t	W/e_0^2
5	½	Rect.	1.39	4	0.606
7	Rising front		1.60	4	0.173
17	1½	40	1.45	4	0 703

From these and similar data it appears that much less corona energy is required to cause sparkover on a rising front than on the crest or tail of a wave; and therefore suggests that the time rate of change of voltage is of considerable importance in causing sparkover.

Mr. Peek has outlined in his paper the possibility of drawing the complete *impulse ratio-time lag* curve if the impulse ratio at the 50 per cent sparking point is known. It is of interest to carry out this suggestion in detail.

The equation of the "standard" test wave is

$$e = E_0 (\epsilon^{-mt} - \epsilon^{-nt})$$

and if the front (f) is short compared with the length (L), then the tail of the wave may be approximated very exactly by

$$e = E\ \epsilon^{-m(t-f)}$$

where E is the crest of the wave. The tail decays to half value at time $t = L$, so that

$$e = \frac{E}{2} = E\ \epsilon^{-m(L-f)}$$

or

$$m = \frac{\log 2}{(L-f)} = \frac{0.692}{(L-f)}$$

If sparkover ceases for an impulse ratio β_1 and after the time t_1 at which the tail of the wave crosses the e_0 line (ultimate sparkover value for unlimited time), there is

$$e = e_0 = E\ \epsilon^{-m(t_1-f)}$$

or

$$\frac{E}{e_0} = \beta_1 = \epsilon^{m(t_1-f)}$$

hence

$$t_1 = \frac{1}{m} \log \beta_1 + f = (L-f)\frac{\log \beta_1}{\log 2} + f$$

But the impulse ratio follows the curve

$$\beta = 1 + \frac{a}{\sqrt{t}}$$

so that

$$a = (\beta_1 - 1)\ \sqrt{t_1} = (\beta_1 - 1)\sqrt{(L-f)\frac{\log \beta_1}{.692} + f}$$

where

β_1 = impulse ratio at 50 per cent sparking
f = front of the wave
L = length of the wave.

Thus on this basis, if the impulse ratio at 50 per cent sparking is known for a wave of given front and length, then the impulse ratio at any time lag may be found. For accurate numerical agreement, β_1 and t_1 should correspond to sparkover on the tail of the wave at a voltage equal to the sparkover voltage of a continuously applied potential.

C. L. Fortescue: Permit me to say in introduction that the rationalization of the insulation from transmission line to substation apparatus has nothing whatever to do with the question of the so-called standard wave. In rationalization what we seek to accomplish is to design the various members of a system in such a way that the strength under any condition of operation will progressively increase from a given point on the transmission line to the apparatus. What is required to determine how this shall be accomplished? The answer to this seems so simple and obvious that I cannot understand why there should be any room for differences of opinion. Obviously what must be determined is how long each member can withstand an applied voltage, beginning from the voltage at which it will just break down under continued application to values as high as are likely to be obtained under operating conditions. In mechanical engineering it is customary to base the strength of various members of a structure on the steady stress required to reach the elastic limit, the members being designed to withstand normal load with a factor of safety depending upon the type of stress to which it may be subjected. In electrical engineering we are somewhat better off in regard to the strength of our insulating members and we may actually test them so as to get information on their behavior for all values of stress and when such data are obtained we have the means for comparing the relative strength of the different members on an absolute basis.

The ability of the member to withstand various values of applied voltage and this ability measured by the so-called time lag or the length of time after the voltage is applied before the member flashes over, are the data required. Having obtained these data on the various members we can very easily compare them as to their relative strength for various values of applied voltage; thus considering the various types of gaps, we find on comparing the sphere gap with the needle gap, both of which have the same flashover value for a steadily applied voltage, that for high voltages the sphere gap is not so strong as the needle gap, that is to say, the sphere gap will not withstand the higher voltage as long as the needle gap. The curve showing the relation between applied voltage and the time required to flashover is the voltage-time lag curve, sometimes called the impulse time lag curve.

As in the case of mechanics it is necessary to devise testing machines by which the stress can be applied and accurately measured. The requirement of such a machine is that it shall be capable of maintaining the stress steadily until rupture takes place and this is true whether we use a mechanical machine for applying stress to a test piece or whether we use an electrical machine to apply stress to an insulating member or spark gap. The curves so obtained are fundamentally characteristic of the member and give all the necessary data as to its strength. The curve of the voltage of the type mentioned as the ideal for the test machine is sometimes called a flat topped wave. It is not possible to obtain an absolutely flat topped wave by any kind of electrical testing equipment but the closer we approach this ideal the more fundamental will be our test results.

I am gratified that there has been such a general discussion of this problem of rationalization. I shall try and reply to the points raised by the various speakers as briefly as possible.

Mr. Austin, in his discussion, suggests that there may be difficulty in balancing various members within 10 or 15 per cent. This, of course, is true to a certain extent but I do not anticipate any serious difficulty. As regards the deterioration of insulators due to smoke and dirt, this need not be considered for the reason that it scarcely affects the flashover value of insulators for time lags below 20 microseconds and longer time lags than this need not be considered. There may be one exception to this, in the case of insulators covered with salt spray where the distribution may be so upset that flashover will take place at lower voltages for a given time lag. Mr. Austin also mentions the fact that the limitation of the voltage in substations by means of arcs is hardly desirable from an operating standpoint. This has been realized for a long time and therefore lightning arresters have been developed. During the past few years, development of the lightning arrester has progressed to such a stage that at present a ceiling voltage as low as 2.5 times the rated voltage may be obtained. These new low ceiling voltage arresters are capable of protecting practically all the present types of substation equipment especially if an effort has been made to rationalize the system insulation.

In Mr. Jones' discussion there is an implication that outages due to direct strokes can be avoided by insulation alone. The results of our lightning investigations in the field show that it would be highly improbable that an insulating structure could be built which could withstand direct lightning potential without flashover. It is necessary to safeguard the insulating structure by various means such as for example the use of ground wires properly placed with low tower footing surge impedance or by means of suitably placed arresters.

Mr. Samuels implies that in connection with the discussions on rationalization there appears to be some confusion. My impression is that the confusion, if such exists, arises not from any intrinsic difficulty in the problem but from lack of straightforward thinking. It is true that there has been a considerable amount of data already published as to the characteristics of different structures that enter into the electrical system.

Some of these data will undoubtedly, in the course of time, have to be revised, especially such data as are being obtained by special wave forms which do not have the required characteristics of rising to a crest value in a very short time and remaining substantially flat through the whole range of breakdown values. The interjection of the question of wave standardization in this problem has been due to a complete lack of understanding of the nature of the problem which is not one of testing the system but is one of procuring the fundamental data which is required for the design of the system. I shall try to answer Mr. Samuels' questions in the order in which he has presented them.

Group A: Shall one part of a system have lower insulation than another part of the same system, and if so what part and how much lower? As I have stated in my reply to Mr. Jones' discussion, insulation is only one element in the problem of protecting the system against lightning The lower limit of insulation of any system is the amount of insulation that will just withstand normal operating surges, such as those due to switching, without flashover. Any insulation above this value may be considered as part of the protective layout to prevent lightning outages. Since induced voltages are probably negligible for transmission lines above 66 kv., for such lines the design of the protective layout against lightning must be considered from the point of view of direct strokes. Three important factors in the design of the ground wire protection are:

1. Proper configuration of ground wires with respect to line wires so that they form an effective shield for the line wires against an oncoming stroke;

2. The proper tower clearances so that all possible discharge paths under these conditions will have the same strength. In this connection it should be noted that while it is desirable to have sphere gap characteristics between the line and tower structure, advantage cannot be taken of improved characteristics to reduce this clearance for the reason that, as I have mentioned in this discussion, a sphere gap having the same 60-cycle flashover as a needle gap will have a lower impulse strength for high applied voltages. For sphere gaps, where the spacing between the spheres is large as compared to the diameter of the spheres, for the same clearances, the impulse value for time lags of the order of one microsecond is not appreciably higher than for the needle gap;

3. The tower footing surge impedance should be rationalized with respect to the tower insulation so as to give the necessary protection. Thus in some cases where it is impossible or extremely costly to get low tower footing resistance it may be more economical to increase the number of insulators to the string and where tower footing surge impedances are extremely low it may be advantageous from an economic standpoint to use fewer insulators on the string.

Following the procedure outlined in the above paragraph, a line designed in this manner would through its entire length give the same degree of protection against lightning, which would not be the case if the same amount of insulation was used at every point on the line. In determining the position of ground wires it would be necessary to provide sufficient spacing from the line wires so that side flash, in case of the ground wire being struck, would be prevented. Unfortunately we do not have as yet sufficient data as to the potential of a lightning stroke when it hits a ground wire to decide definitely what this spacing should be, but assuming that the potential of ten million volts will be produced at the point where the stroke hits, the proper distance between ground wire and line wire should be of the order of 32 ft. which is the needle gap spacing which will just flash over with 10 million volts applied for one microsecond. However, it may not be economically feasible to use such a large spacing, especially for low transmission voltages.

Group B: What shall the insulation rating of each part be? This has already been answered under Group A for the case of line construction using ground wires. Where lightning arresters are used the length of string to give the same level of protection at different distances from the arrester has already been given in my paper.

Group C: What definite commercial test method shall be used to determine whether or not a piece of equipment has the specified insulation value? Voltage-time lag curves have been obtained and published for practically all of the elements that enter into the design of a system but in cases where such are not available and the 60-cycle flashover is known, the voltage time lag curve can be approximated from the known data.

The sub-questions appearing under Group A,

1. What shall be the flashover value of transformer bushings in relation to the insulation of transmission lines which are connected to the same bus? The best answer to this question is perhaps to insulate the transmission line to whatever the designer wishes, then limit the voltage in the substation where the bushing is located by (a) lightning arresters or (b) protective gaps which may take the form of reduced insulation or gaps of various natures.

2. What shall be the relation of the insulation of the transformer itself to that of its bushing? The transformer insulation strength should be coordinated with that of the bushing, past experience being given proper consideration in the coordination.

3. What shall be the insulation value of a breaker bushing in relation to that of the transformer bushing? There is little need for having a bushing of a different flashover value for the breaker and for simplicity it is advantageous to have the two bushings interchangeable.

4. What shall be the insulation value of an insulator on a bus to that of the bushing on transformers and breakers? As mentioned before, the substation should be protected by lightning arresters and gaps or a combination of the two and if the substation is to be protected the breakdown values of those gaps should be well below the bushing and bus insulation. If they are well below, it is then optional with the designer of the substation as to how much margin he wishes to have between protecting gaps and the various forms of insulation in the substation. This variation should perhaps be governed by the designs of the insulators and other equipment. It is essential only that there be a comfortable margin between the operating protective device and the flashover value of the insulation.

5. What relation shall there be between the insulation value of an insulator on a disconnect or a branch in relation to that of the bus or the bushings? This question is also answered by the answer to question (4).

6. What part shall be assigned to the lightning arrester in this discussion? From the author's point of view the lightning arrester plays the stellar role. The lightning arrester is the only device at present which can give satisfactory performance under repeated surges without causing outages, therefore, rationalization of the substation should be so carried out that the lightning arrester will function before any apparatus in the substation breaks down.

7. When shall the line insulation close to a station be made lower than the line insulation on the rest of the line? This should be done where protective gaps are not used. Where lightning arresters of proper characteristics are installed in the proper location it may not be considered necessary but it is advisable as a back-up protection in case the lightning arresters are removed for inspection.

Referring to Mr. Wallau's discussion, he calls attention to the difference in values obtained by General Electric and Westinghouse engineers for waves that are presumably similar and then he later on gives these inconsistencies as a reason for agreeing with Mr. Sporn's proposal to standardize wave forms on the basis of what is known about natural lightning waves—whatever the word natural may mean in this connection. One might just as well recommend to structural engineers to design bridge members on the basis of the natural stress they get under heavy

traffic conditions where a large number of automobiles start and stop suddenly on the bridge. What we are concerned with is relative strength, not the actual ability to withstand a particular wave form. A fundamental basis for obtaining relative strengths is to measure the time required to flashover when different values of voltage are suddenly applied to the insulator under consideration. The inconsistencies that Mr. Wallau calls attention to are not the result of the wave form but are due to differences in methods of measuring voltage and time lag. These discrepancies are not very serious and need not delay the application of the principles outlined in these papers. No doubt when men first began to measure the strength of materials, wider discrepancies than these arose but they did not prevent the development of the steam engine and a few other things that have forwarded civilization.

The development of methods and machines for measuring the strength of materials has been in progress for over a century and our friends expect us to reach the same state of perfection in measuring impulse strengths of insulating structures in three years of development. I would be surprised if in 10 or 15 years from now no discrepancies would be found in the measurements obtained by different bodies.

Let me once more reiterate that the so called standardization of wave form has nothing to do with the fundamental data on voltage time lag of insulating structures. About all that can be said in favor of a standard wave to represent lightning is that it might be of value in testing a system or equipment to find out whether it will withstand successfully, so called natural lightning. For obtaining design data, for rationalization, etc., it is of little value.

The specific information which Mr. McEachron wants concerning Fig. 1 is as follows: The number of insulators used in the test was four suspension insulators of the ball and socket type, 10 in. in diameter and 5¾ in. spacing. The arrester was of 73 kv. rating. The arrester was for non-grounded neutral service. It is of the autovalve type constructed of disks and mica separators and should not be confused with the new porous block arrester which limits the voltage to an even lower value. The applied surge is a laboratory representation of a traveling wave. By laboratory representation is meant that there were 500 ohms in series with the surge generator to represent current values as would appear on transmission lines. The laboratory current wave corresponds closely to that which would be found upon an actual transmission line if the voltage wave were similar to that shown in Fig. 1. In regard to Mr. McEachron's remarks in connection with the use of arresters for protecting transmission lines, I am sure that we are generally in accord on this question. I thought that I made it quite plain that it was necessary in considering such protection to determine a certain level and say for example that we will design this line so that any surge below this level will not flashover the insulators. Quite obviously a direct stroke to the line, as Mr. McEachron points out, at any point away from the arresters will cause a flashover at that point if the lightning stroke is sufficiently severe. In order that this last statement may not be misconstrued we may point out that it is quite probable that many of our smaller surges are due to side flashes from the main lightning stroke which do not cause severe surges.

Mr. Bewley's discussion on the energy of flashover deals with only two factors essentially, that is the voltage and the time. It is altogether erroneous to talk of energy of flashover in terms of purely voltages and time. Current oscillograms have been made of flashover with astonishing results. The most important of this work has been published in the paper by Messrs. Torok and Fielder and from the oscillograms in that paper it is evident that the current does not vary directly with the voltage and therefore it is almost out of the question to say anything of the energy of sparkover unless cathode ray oscillograms of the currents involved are made.

F. W. Peek, Jr.: It is futile to hope for an exact or perfect lightning wave from measurements on transmission lines. It is quite obvious theoretically that an infinite variety of waves may occur due to lightning. Of the very *many* waves measured, no two have been found that are exactly alike. This does not mean that standard waves for testing insulators and for coordination cannot be wisely selected at this time. Fortunately, it is not as complicated as it seems. Observations of lightning over many years show there are certain typical effects.

For high voltage lines the lightning sparkover of insulators is always much higher than the sixty cycle sparkover. In fact, on 220-kv. lines we have found that the ratio of the lightning sparkover to the sixty cycle sparkover, the impulse ratio, is usually over 1.8. These effects, which may be very severe because the voltages rise to such high values, may be produced as I have shown in my paper, by a number of different waves. I have found the ½/5 wave very convenient as a preferred or reference wave to produce these steep wave front effects.

Waves giving the effects of moderate steepness may occur at lower voltages and lower impulse ratios. Such waves become of increasing importance as the insulation of the line is decreased. The effects can be produced by full wave tests with a 1½/40 wave. It is my opinion that lightning characteristics of insulators and coordination are sufficiently determined by these two waves. I would, therefore, recommend that these waves be adopted as preferred waves.

I cannot conceive of the adoption of preferred waves in any way having a narrowing effect on research. Such waves should in no way influence types used in research and, as reference points and means of comparison, would be of great value. There has been an expression of pessimism by several in this discussion on the available knowledge of the lightning strength of solid insulation. I do not hold this view since we are able to predict, with great accuracy as shown by tests, the lightning strength of such complicated insulation structures as transformers. The non-resonating transformer has also simplified matters.

I have used, and strongly endorse the use of the cathode ray oscillograph whenever desirable. However, many of the smaller laboratories do not have cathode ray oscillographs. For this reason standard tests that are so simple that they can be performed accurately with sphere gaps as well as with the oscillograph are to be very highly commended.

The difference between the impulse curves from the different laboratories is due to attempt at comparison without consideration of all the variables. Obviously, two waves, each 20 microseconds in length but with different fronts, should not give the same voltage values.

Mr. Fortescue concludes by some formidable looking mathematics that induced voltages cannot be high and that all transmission line troubles must, therefore, be caused by direct strokes. A casual examination of his calculation indicates that the results are based upon a very high point charge and not, as stated, on a sphere cloud. If the calculation is corrected and actually based upon the sphere cloud it will be found that the results will indicate induced voltages of really dangerous values.

It is my opinion that our troubles result from both induced voltages and direct strokes. The direct strokes become of relatively increasing importance with increasing insulation.

I wish strongly to endorse the coordination method outlined in the paper by Messrs. Montsinger and Dann. In this connection, the remarks that Mr. McEachron has made are of interest.

Philip Sporn: Mr. Jones has commented on my criticism of the failure of the various insulator manufacturers to furnish data as to 60 cycle flashover of similar insulators that agree, and has pointed out that Mr. Austin has always attempted to take these factors into consideration in the data he gives. He believes that insulator strings have the same flashover characteristics under varying degrees of humidity as the needle gap and he

therefore takes care of the situation by expressing his 60 cycle flashover value of insulators in terms of spark gap values.

Disregarding for the purpose of this discussion the lack of accepted data in regard to spark over value of needle gaps under different conditions of humidity, it cannot be too strongly emphasized that Mr. Jones' facts themselves show the absolute unsoundness of Mr. Austin's practise. If a rod of a particular metal has an unusually large coefficient of expansion then a yard stick made of that metal is the very one *not* to use to measure the length of the rod in question under different conditions of temperature; in other words, the needle gap of all gaps is the one not to use as a calibrating means for determining 60 cycle spark over value of insulators.

I have I believe anticipated in my paper and answered Mr. Cox's main objections to the adoption of a standard impulse wave. However, I shall briefly summarize these again:

Admitting that complete volt time characteristics of all insulating media and structures is desirable it is a fact that such data will take many years to assemble. The proposed standard impulse test waves would enable the obtaining of these data (although these would give only four points—the 60 cycle value being of course the fourth point—on the volt time curve) in much less time. If the term "Standard Test Wave" is objectionable we might call them "Recommended Test Waves." This ought to eliminate a number of the objections. There has of course been no suggestion made as yet to alter the existing A. I. E. E. Apparatus Standards so as to call for an impulse test by applying one or all of the proposed test waves; nevertheless I am confident that we are definitely coming to it. It may be that this is the real reason back of Mr. Cox's objections.

I have always advocated the use of the lightning arrester where the economics of the situation permitted, hoping that some day it would demonstrate its complete economic justification while admitting that so far it had failed to do so. Mr. Treat's suggestion of *two* lightning arresters is a bit too much for me. If two arresters, why not three?

V. M. Montsinger: The idea seems still to prevail that the manufacturers of transformers want the operators to reduce the line insulation near the station. While this might generally result if standard transformers are to be used on account of the practise of over-insulating lines there is no occasion why higher insulated transformers cannot be used leaving the line as it is. In fact the proposed rules provide for this. It is well to point out again that it has never been the intention of the transformer subcommittee to dictate the level of line insulation even at the station, but rather take this as the stating level and build up to the transformer.

It is to be regretted that Mr. Sporn takes a pessimistic view on what is being accomplished in the line of coordination. We feel that a great deal has been done since he presented his memorable paper at Springfield in 1928. Perhaps the work has not been carried out along the exact lines he would prefer but since it has become standard practise with all progressive utility companies to use the best available data in making new station layouts and in fact in many cases in revamping existing layouts to obtain proper coordination we should feel encouraged.

As to the suggestion of incorporating our recommendations in A. I. E. E. Standards No. 13, Part II, in view of the policy adopted within the past year on Recommendations on Operation of Transformers does not belong in the main rules but rather should be combined with the new pamphlet, No. 100, which has just been published by the A. I. E. E. Part I, in some form, should be incorporated in Standards No. 13. The impression seems to prevail that once a rule is put into effect it cannot be changed. For the past few years there has existed a subcommittee which is so set up that desirable changes can be effected in very short time. It is the purpose of the Transformer subcommittee to make Standard No. 13 reflect up-to-date practises and we feel that it really does. Nevertheless as long as the recommendations are being followed in practise it does not matter so much whether or not they are in one of the Standards. If we wait until the recommendations are perfect they may never be standardized.

G. D. Floyd: I quite agree with Mr. Palueff that the relation which he has suggested between the number of flashovers and the height of conductor, etc., is only an expression of the tendency of effects of the various factors. He showed that for our Gatineau line the average number of flashovers worked out to 1.48, compared for the service record for 1929 of 1.75. For the 1930 season to date (Sept. 8th) there has not been a single flashover, which indicates that any formula set up to forecast a result such as the above must not be taken too literally, and in any case should be averaged over as great a circuit mileage of line as possible, and compared with the average flashover taken over a number of years operation.

Any explanation of why the co-ordinated insulation at our Leaside Station did not protect the transformer would be only conjecture, with the information available. A number of possibilities might be given, some of which are:

1. Direct hit on station bus very near transformer.
2. Insulation failure of lifting rod on 220-kv. circuit breaker, which was found shortly after, and appeared to be similar to the characteristic fracture of wood by lightning.
3. Incorrect co-ordination.
4. Possibility that it is not possible to protect apparatus against all incoming surges, of which the surge in question was one, by co-ordination only.

The tower footing resistances have been measured from the station out some distance, and these are quite low, of the order of 10-20 ohms. The station ground resistance is also extremely low, being a few hundredths of an ohm. The station ground wires are connected to the four line ground wires, which are of high conductivity, so that it seems reasonable to assume that the whole ground wire network and towers connected to it, are substantially at true ground potential.

Mr. McEachron does not state why he believes that the insulation level should be based on the gap rather than the arrester. Assuming that it is the fact that arrester operation at the higher values of surge current is still unknown, it seems that even with this handicap it would still be preferable, because of the straight line characteristic of the arrester for voltages of practically all durations. The spillway gap, by its very nature, has a characteristic which resists relatively high voltages if they are of short duration, and it cannot be expected that the solid and liquid insulation of a transformer will have even approximately the same volt-time characteristic as the gap. Therefore, the arrester is the logical unit around which co-ordination can be centered, and if some of its performance characteristics are still unknown, every effort should be made to ascertain them.

The subject matter of a great deal of the discussion of these papers indicate that we have not yet obtained sufficient information on the fundamentals of the problem to make more than an educated guess as to how best to solve it. Much of the discussion was confined to dissertations on the mechanics of the lightning bolt and the possibilities of direct hits and induced strokes, as well as to the relative merits of various laboratory methods, and to discrepancies between the same measurement made at different places. Until a majority of these things are established beyond doubt it will be necessary to proceed with caution, and not disturb the co-ordination that has become established by experience, without good and sufficient reason.

A. E. Silver: While the several papers and discussions on the subject of insulation might indicate rather wide differences in results obtained from research, ideas and reasoning are becoming better crystallized. As knowledge concerning the transient voltages affecting the performance of lines and apparatus is extended, greater agreement on the fundamentals can be expected

and satisfactory solutions to the insulation problem will be forthcoming.

The data which have been previously published on insulation characteristics as well as those contained in this symposium of papers, are all helpful to the intelligent use and coordination of insulation. Nevertheless, considerable work still remains to make them reasonably complete even for insulations now in common use. It is hoped that complete volt-time curves, or sufficient information for calculating them with reasonable accuracy, will soon be made available and that these data will be extended and modified in keeping with new knowledge as it is gained.

A word of caution might be spoken regarding attempts to write empirical formulas expressing the performance of lines with varying amounts of insulation, the influence of overhead ground wires, the relative frequency of occurrence of surge voltages of different magnitudes, attenuation of lightning voltages, and averaging of lightning surge wave shapes as they have been measured on lines of limited insulation strengths, etc., from data which are only partially reliable or representative.

The problem of insulation coordination is important and must be correctly solved and any compromising which may be resorted to, though expedient for the interim, must avoid the appearance of finality.

H. L. Melvin: Messrs. Lewis, Treat and McEachron have commented on the application of lightning arresters in the coordination problem while Mr. Peters is concerned regarding the possible influence of establishing successively higher insulation levels in a station on the insulation strength requirements of apparatus.

While lightning arresters or voltage limiting devices may play an important part in the coordination of system insulation, particularly when apparatus of inherently lower lighting insulation strengths are component parts, they are by no means a substitute for coordination. It should also be remembered that an economic justification must be established for the installation of arresters based on the protection afforded. Should such a device function perfectly to protect equipment when subjected to the most severe lightning discharges, then a coordinated system might have its component parts at practically the same insulation levels, which might be determined by consideration of generated overvoltages and switching surges. Pending the development of entirely dependable devices, or the knowledge which will permit of designing lines and stations so that the lightning current, which arresters may be called upon to discharge can be limited to the capacity of the devices, and for those situations where the installation of such arresters may not be justified, coordination of station insulation strengths by arranging the parts in successively higher steps would seem entirely logical and warranted. The application of arresters with a recognition of their limitations and for the purposes suggested by Mr. McEachron, would seem to be a very satisfactory procedure for the present at least.

The differentials suggested of 10 per cent between the line spillway and bus, 5 per cent between bus and apparatus bushings and the apparatus itself with a sufficient margin above its bushings, might lead to somewhat higher levels for stations and apparatus than present common practise, provided the spillway levels are established by insulation equivalent to the numbers of suspension insulator units as recommended by the Transformer Subcommittee. However, if the equivalent gap values as recommended by the Subcommittee are used as bases, the insulation levels would be somewhat lower. The data given in the paper by Messrs. Johnson and Bundy are quite illuminating in this respect, as the spillway gap settings used for 66-kv. and 110-kv. are even lower than proposed by the Subcommittee and evidently switching surges are not the cause of flashovers of these gaps. The point which it is desired to make is that, a proper or satisfactory value for the spillway has not been established due to insufficient knowledge regarding the values and character of surges arising within the system, but positive differentials between the various levels do seem essential if the flashovers which may occur at stations are to be localized at predetermined points. Furthermore if present trends and practises are incorrect or are not established upon sound bases, then the fundamental data should be obtained before final standardization is undertaken.

Attention should be called to the relatively slight consideration which is given to the distribution voltages in the studies of insulation and its coordination, whereas this part of the system is in many cases equally as important as the transmission. It will also be observed that rather glaring inconsistencies exist in practise, which may well be improved upon from the knowledge and data already available.

I would like to make the following general comments regarding the entire group of papers. They constitute another material contribution both of useful data as well as theoretical and practical discussion of this important problem. The unknown features have been well outlined and there seems to be little question but what they will be satisfactorily solved within a relatively short period. Complete knowledge of the lightning and surge voltage problem will not only make it possible to effect material improvements to service but economic benefits will be derived.

At the present time there seems to be possibly too much of a tendency among operating engineers to advise the manufacturers regarding the design of apparatus, likewise the manufacturers may be inclined to concern themselves unduly with transmission line design. It would seem therefore that if the operators would concentrate upon the task of discovering what are the magnitudes and characteristics of the surge voltages arising within the system and of natural lightning imposed upon the circuits while the manufacturers are devoting themselves to the design of insulators, apparatus and protective devices to give satisfactory service with these voltages applied (the two groups working in extremely close cooperation), a more satisfactory and practical solution to the entire problem will be found.

Long Distance Cable Circuit for Program Transmission

BY A. B. CLARK[1]
Member, A. I. E. E.

and

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Synopsis.—The rapid growth of the telephone cable network in this country has made it desirable to develop a system whereby this network may be utilized to transmit programs for broadcasting stations over distances upwards of 2000 miles. Such a system has recently been developed and given a trial on a looped-back circuit 2200 miles long with very satisfactory results. It transmits ranges of frequency and volume somewhat in excess of those now handled by the open-wire circuits which are used for program work, and also in excess of those handled by present-day radio broadcasting systems when no long distance lines are involved.

The paper deals first with the transmission requirements of broadcasting systems and then gives a description of this new cable system.

* * * * *

As discussed in two recent papers,[3] one of which was presented before this Institute, telephone circuits are now extensively used for chain broadcasting. Radio broadcasting stations covering various local areas in the United States are connected together by wire circuits so that programs are delivered simultaneously to all of them. Thus, it is possible to deliver a program to the whole nation at once. About 35,000 miles of telephone circuits are now being regularly utilized for this service and about 150 radio broadcasting stations receive programs from one or more of the chains of wire circuits.

Today practically all of this service is being furnished by means of open wires using voice-frequency channels. Long distance cable routes are growing rapidly and are supplementing the open-wire routes, particularly those carrying very heavy traffic. Fig. 1 shows the long distance cable routes now in use in the United States, together with the additional routes proposed for installation within the next few years. The advantages in placing some circuits in these cables which will adequately handle program transmission service were evident and led to the development described in this paper.

Because of the special characteristics which program transmission circuits must possess it was necessary to develop an entirely new type of cable circuit, in which the method of placing the wires in the cables, the type of loading and all of the apparatus, including amplifiers and distortion correcting apparatus for both amplitude and delay, differ radically from other cable circuits. The development was recently completed and a trial installation made in which wires were looped back and forth in the cables between New York and Pittsburgh so as to produce a circuit 2200 miles in length. Tests were made on this circuit over a period of several months and very satisfactory results were obtained. It is, therefore, planned to make extensive application of this system and eventually program circuits may be provided in cable over practically all of the long toll cable routes.

So as to appreciate what is involved in the design of this system there will first be presented a discussion of the transmission requirements. Following this, the new system will be described and its more important transmission characteristics set forth.

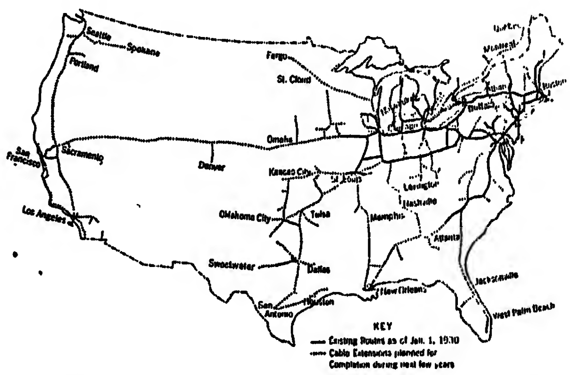

FIG. 1—MAIN TOLL CABLE ROUTES OF UNITED STATES AND CANADA

TRANSMISSION REQUIREMENTS

For program transmission the ideal, of course, is to provide a transmission line such that no distortion whatsoever will be caused to program material transmitted over the line whatever be its length. Ideally also, program pickup apparatus, radio transmitters, radio receivers and loudspeakers should be such that the program delivered from the loudspeaker should sound exactly like the original program delivered to a direct listener in the best location. To meet this ideal, however, would require that the whole audible range of frequencies, extending from about 20 to 20,000 cycles, and a tremendously wide range of volumes representing power differences of more than a million-fold be handled without any distortion whatsoever.

Actually the radio art is far from attaining this ideal.

1. Toll Transmission Development Engineer, Am. Tel. & Tel. Co., New York, N. Y.

2. Telephone Engineer, Bell Telephone Laboratories, Inc., New York, N. Y.

3. F. A. Cowan, *Telephone Circuits for Program Transmission*, presented at Regional Meeting of S. W. District of A. I. E. E., Dallas, Texas, May 7-9, 1929, A. I. E. E. TRANS., Vol. 48, 1929, p. 1045; A. B. Clark, "Wire Line Systems for National Broadcasting," presented before the World Engineering Congress at Tokio, Japan, October, 1929, *Proceedings of I. R. E.*, November 1929, *Bell System Tech. Jl.*, January, 1930.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

It does not seem reasonable, therefore, to provide lines very much superior in transmission performance to the rest of the system since this would unnecessarily increase the cost for providing the service. However, telephone lines represent a fixed investment which must remain in service for many years in order to keep costs within reason and, furthermore, it is, in general, not practical to change the transmission characteristics of the lines once they have been installed. It is, therefore, necessary to take into account the fact that the broadcasting art has considerably improved in the past and is likely to improve in the future and provide telephone lines of sufficiently good characteristics to anticipate the improvements which are likely to come within a reasonable period of time.

These general considerations have led to the adoption of the following as practical standards of performance for the new cable system:

1. Frequency range to be transmitted without material distortion—about 50 to 8000 cycles.

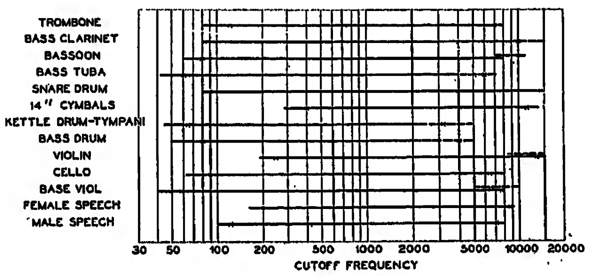

FIG. 2—SUMMARY OF IMPORTANT RANGES REQUIRED FOR DIFFERENT INSTRUMENTS

——— Actual tone range
– – – – Accompanying noise range
× Cut-off frequency at which 80 per cent of the observers could detect the filter

2. Volume range to be transmitted without material interference from extraneous line noise—about 40 db. which corresponds to an energy range of 10,000 to 1.

Some of the more detailed considerations which have led to the setting of these standards will now be given.

Frequency Band. Fig. 2 gives some data in regard to the frequency range required for different musical instruments as well as speech. These data were obtained in the Bell Telephone Laboratories using an arrangement capable of picking up and reproducing practically the whole audible frequency range. Certain low-frequency instruments, such as organ pipes and bass drums, were not included in the tests owing to laboratory limitations. A number of observers listened to the reproduced material, first, when practically the whole frequency range was transmitted and, second, with either the high frequencies or low frequencies cut off by means of filters. The observers endeavored to note whether there was any perceptible effect when the filters were introduced but did not attempt to determine whether introducing the filters made the reproduced material sound more or less pleasing.

Referring to the figure, it will be noticed that at the lower frequencies little appears to be lost by cutting off frequencies below about 50 cycles. At the upper frequencies, however, with certain of the musical instruments something is lost by cutting off frequencies above 8000 cycles. Hissing sounds, sounds of a percussion nature, and sounds of jingling keys, rustling paper, etc., appear to be most affected by cutting off the high frequencies.

Tests have shown, however, that when the frequency range 50 to 8000 cycles is transmitted with very little distortion within the band the results obtained are very pleasing. The ordinary observer without making direct comparison tests is unlikely to detect the absence of the higher frequencies.

From the standpoint of radio transmission there will probably be some difficulties in handling the 8000-cycle range which has been tentatively set as a standard for the cable line. Each radio station, theoretically at least, is now being allowed only a 10,000-cycle band of frequencies and, since both sidebands are transmitted, each band is fully occupied when transmitting 5000 cycles. Since adjacent frequency ranges are not assigned to stations in the same locality, a certain amount of spreading out is, no doubt, tolerable, so that those listeners who are close to broadcasting stations should, in general, be able to pick up the 8000-cycle range without undue interference from other stations. The more distant listeners will have trouble if their sets take in the complete 16,000-cycle band required to handle, on a double-sideband basis, the 8000-cycle program range. Letting in this wide frequency range will bring in increased interference from other stations and will also increase the atmospheric interference.

In spite of this increased trouble which the distant listeners will have, it can no doubt be argued that it will do little harm for the radio stations to put out the full 8000-cycle band. The nearby listeners, if they have very good sets, will in general be able to appreciate this, while the distant listeners, if their sets are arranged to receive only a 5000-cycle band, should receive only slightly more interference from wide-band stations occupying adjacent frequency bands.

Evidently, if the frequency range were doubled so as to furnish the listener with practically the whole audible range of frequencies, these radio difficulties would be exaggerated. It seems certain that, if radio stations were to handle the whole audible band of frequencies, a reassignment of frequency bands to these broad-band broadcasting stations would be called for and also quite probably these radio stations would be forced to resort to single sideband transmission.

It is not sufficient merely to fix the limits of the frequency band. Limits to the allowable distortion within it must be established. Tests have indicated that it is desirable that different frequencies within the transmitted band should not suffer attenuations differ-

ing by more than about 5 db., corresponding to power differences of about three-fold.

The transmission delay[4] suffered by different portions of the frequency band must also be considered. This is necessary because, when transmission over long distance lines is involved, this delay tends to be different for different parts of the frequency band and the distortion produced is a function of the frequency-delay characteristics. Tests have indicated that the high frequencies, say those in the range 5000 to 8000 cycles, should not suffer delay in transmission over the line more than 5 to 10 milliseconds greater than the delay suffered by frequencies in the neighborhood of 1000 cycles. However, at the low end of the scale more delay may be tolerated: for example, 50 cycle waves may be delayed as much as 75 miliseconds more than those in the neighborhood of 1000 cycles without noticeable deterioration in quality.

Requirements must also be imposed as to "linearity" of the transmission, that is, constancy of efficiency with different current strengths. If the transmission departs too much from "linearity" several disagreeable effects may be produced: (1) Spurious frequencies which are by-products of the true frequencies will become large enough to be annoying, (2) strong sounds will not be reproduced as well as weak sounds, and (3) when weak sounds are transmitted along with strong sounds the strong sounds will tend to obliterate the weak sounds.

In the design of this program transmission circuit the criterion was adopted that transmission put over the circuit at the maximum prescribed volume level must not sound appreciably different than transmission put over the circuit at a considerably lower level, at which lower level the non-linear distortion is negligible.

Volume Range. A favorably-seated listener to a high-grade orchestra is treated to a wide range of volumes. Opinions differ as to just how wide a volume range can be appreciated by such a listener, but it seems certain that it is at least 60 db., corresponding to a power range of one million to one. The human ear can hear volume ranges in excess of 100 db. corresponding to a power range of ten billion to one. For loudspeaker reproduction it has been found that a room must be particularly quiet in order to be able to appreciate a volume range of 60 db. Rooms in three-quarters of the usual residences are probably too noisy for a volume range as great as this to be appreciated. A 40-db. volume range, corresponding to a power range of 10,000 to 1, can be appreciated in most rooms where radio listening is done and is quite satisfactory for most musical selections.

From the standpoint of design, the maximum volume of a wire program transmission system is limited by the requirement that the program must not be allowed to spill over unduly as crosstalk into neighboring circuits which may be carrying telephone messages or other programs. The volume may also be limited by the requirement that serious non-linear distortion be not introduced by effects produced in the vacuum tubes of the amplifiers or in any magnetic-core coils either in the apparatus or in the line. On the other hand, the minimum volume which a wire program circuit can handle is limited by the tendency of the noise present on the circuit to annoy the listener when the program volume is very weak. Crosstalk from other circuits into the program circuit also enters as an important consideration, since radio listeners must not be able to pick up intelligible conversations during those times when the program volume is very weak or when actual pauses occur in the programs.

From this, it is seen that the matter of widening the volume range of a wire program transmission system involves not only added cost to keep non-linear distortion and noise within limits but also, and perhaps even more important, added cost to isolate the circuit from other circuits on the same route.

From the standpoint of the radio part of broadcasting systems, handling very wide volume ranges also presents difficulties. Radio transmitter and other radio equipment noises become more serious as the volume range is widened. More important, however, widening the volume range without corresponding increase in the radio transmitter capacity reduces the effective range of a radio broadcasting station, since this increases the tendency for the faint parts of the programs to sink below the level of atmospheric and receiver-set noises.

At present it is understood that most radio broadcast programs where no long distance wire circuits are involved are being delivered with a volume range of about 30 db.[5] In order to anticipate improvements which may come in the broadcasting art, however, it has seemed desirable to provide wire circuits in cable which will handle a wider volume range than this and, accordingly, 40 db. has been taken as a working standard. This volume range appears to satisfy almost everybody with the possible exception of some who listen to broadcasts of symphony orchestras and the like. With the present limitations of volume ranges to about 30 db., there has been some complaint that much of the artistic quality and effectiveness of broadcasts of such high-grade music has been lost because of the fact that the operator manipulating the volume range control seemed to reduce the range an undue amount.

Studies are now under way looking toward systems which will compress the volume range transmitted over the line and expand it at the far terminal, but possible applications to radio systems may be difficult since receiver characteristics need to be considered.

If some volume range compression and expansion

4. "Delay" as used in this paper has the same significance as "envelope delay" used in literature on phase distortion. It is defined as $d\beta/d\omega$ where β is the phase shift and ω is 2π times the frequency.

5. O. B. Hanson, "Volume Control in Broadcasting," *Radio Broadcast*, March, 1930.

system is not employed, ability to handle a materially wider volume range can only be obtained with considerable difficulty. In the radio part of systems it will require reductions in radio transmitter noises and involve loss in the effective range of radio stations, unless higher powered transmitters are employed. In the wire part of systems it may involve the use of amplifiers and loading coils capable of handling more power, means for materially reducing the crosstalk coupling between circuits and also means for making the program transmission circuits more quiet.

Description of New Cable System

In this program transmission system the nominal telephone repeater spacing of 50 miles, common with message telephone circuits, is retained. The pilot-wire regulator system which compensates for changes in average temperature) introduced by the preceding repeater section.

2. A delay equalizer which corrects for the difference in delay at different frequencies introduced by the preceding cable section.

3. A one-way amplifier introducing sufficient gain to overcome the line loss, together with the added losses introduced by the attenuation and delay equalizers.

At the regulating repeater stations the arrangement is the same as at the non-regulating stations, except that another stage is added to the amplifiers. This stage includes a potentiometer associated with relays controlled by the master pilot-wire mechanism, the whole being arranged so as to compensate for the changes in transmission loss of the cable pairs caused by temperature changes.

In the lower part of Fig. 3 is shown a transmission

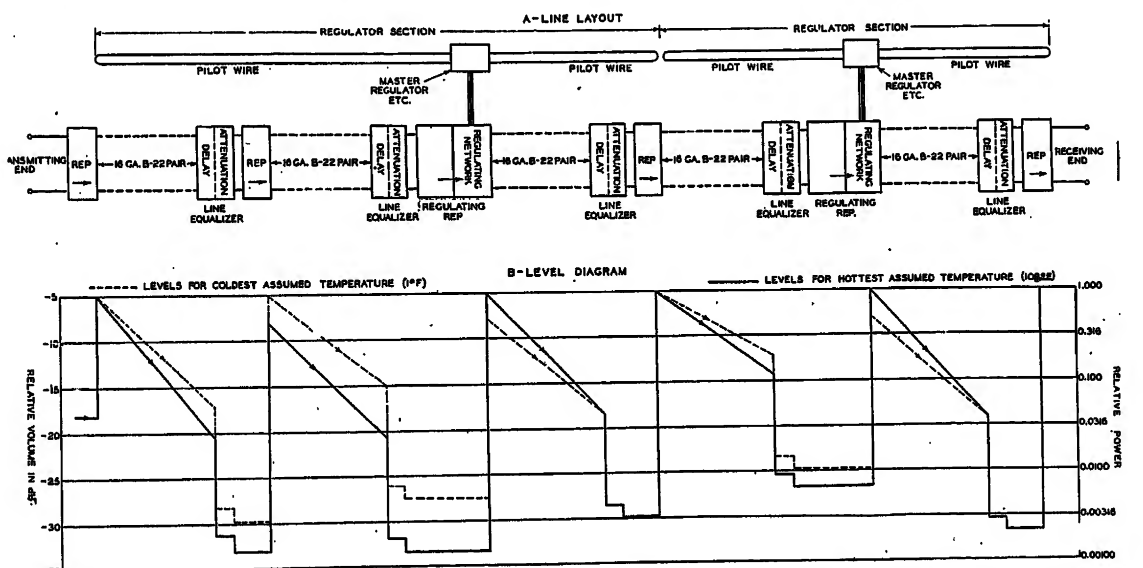

Fig. 3—Typical Line Layout and Level Diagram for B-22 Program Transmission System

transmission caused by temperature changes in message circuits is also used for the program circuits.[6] The diagram in the top part of Fig. 3 shows several hundred miles of program transmission circuit, illustrating how it is divided up into repeater sections and pilot-wire regulator sections and also indicating the principal pieces of equipment located at the repeater stations.

As indicated on the diagram of Fig. 3, there are two classes of repeater stations, known as regulator stations and non-regulator stations. At the non-regulator stations the repeater gains are maintained at fixed values while at the regulator stations they are varied under control of the master pilot-wire regulating mechanism in such a way as to compensate for the transmission variations of the cable conductors caused by temperature changes.

At each non-regulating repeater station are placed:

1. An attenuation equalizer which corrects for the attenuation differences at different frequencies (at

6. A. B. Clark, *Telephone Transmission Over Long Cable Circuits*, A. I. E. E. Trans., Vol. XLII, 1923, p. 86.

level diagram, from which can be noted the losses and gains introduced by the different parts of the system, for a frequency of 1000 cycles.

Cable. The transmission paths are provided by means of 16 B. & S. gage non-phantomed pairs having a capacitance of 0.062 microfarad per mile. These pairs are loaded with 22-millihenry inductance coils spaced 3000 ft. apart. Present long distance message telephone circuits in cable have loading coils spaced 6000 ft. apart. The nominal cut-off frequency of the new circuit is about 11,000 cycles, permitting effective transmission of a frequency band extending up to about 8000 cycles.

The nominal impedance is about 800 ohms and the attenuation per mile, at 1000 cycles and average temperature, about 0.24 db. Fig. 4 shows the attenuation at average temperature plotted as a function of frequency, while Fig. 5 shows the line impedance.

Fig. 6 shows how the cable circuit attenuation varies with temperature at different frequencies. As will be seen from the curves, temperature change produces

effects not only in the series losses but also in the shunt losses. The series losses are changed largely because the resistance of the copper cable conductors changes with temperature and to a smaller degree because of changes in the effective resistance of the loading coils. The shunt losses change with temperature due largely to changes in the conductance losses and, to a lesser extent, changes in the cable capacity with temperature. The conductance loss is approximately directly proportional to frequency so that it has maximum effect at the highest frequency. The effect of temperature on the conductance loss is opposite to the effect of temperature on the series loss so that increase of temperature reduces the shunt loss.

The matter of securing the necessary electrical separation between the 16-gage program transmission circuits and the other circuits contained within the same lead sheath involved particular study. The use of shielded pairs was considered. Such use of shields, however, would very greatly increase the space occupied

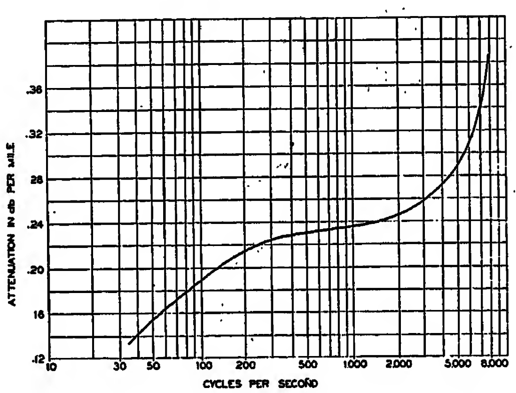

Fig. 4—Attenuation-Frequency Characteristic for 16-Gage, B-22 Cable Pairs at 55 Deg. Fahr. Terminated in Characteristic Impedance

by each program circuit and, therefore, considerably increase the cost. By careful design of the cable and control of methods of splicing, it was found possible to vaoid the use of shields. It was not found practicable, however, to make use of the phantom possibilities on the program pairs.

The method adopted was as follows: Restrict transmission over a particular 16-gage program transmission pair, as a general proposition, to one direction only. Place the program pairs assigned to transmission in one direction among the 19-gage quads used for four-wire transmission paths going in the same direction, and the program pairs transmitting in the other direction in the oppositely-bound four-wire group. Fig. 7 shows a cross-section of a typical cable containing six program transmission pairs, three for transmission in each direction.

Loading Coils. The 22-millihenry loading coils used on the program transmission circuit have cores of compressed powered permalloy, which is the magnetic material now generally used in the Bell System loading coils.[7] Their over-all dimensions are the same as those of the loading coils for the ordinary telephone circuits in toll cables.

Typical effective resistance-frequency curves for the loading coils are given in Fig. 8; these curves include current magnitudes greater than those involved in program transmission service. The core eddy current losses, varying with the square of the frequency, are principally responsible for the resistance increase at the

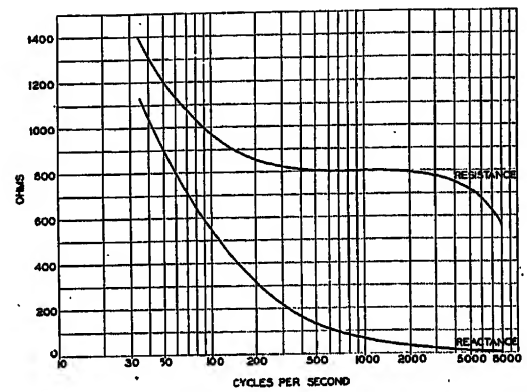

Fig. 5—Mid-Coil Characteristic Impedance for 16-Gage, B-22 Cable Pairs at 55 Deg. Fahr.

higher frequencies. The increase of attenuation with frequency caused by these core losses is readily corrected, however, by the attenuation equalizers which, as described later, also correct for the attenuation-frequency distortion caused by other factors in the cable circuit.

Owing to the low hysteresis loss of the compressed powdered permalloy material, the non-linear distortion introduced by the loading is inappreciable within the

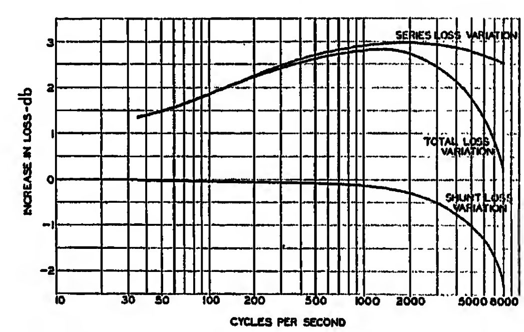

Fig. 6—Attenuation Variation of 100 Miles of 16-Gage, B-22 Loaded Cable Circuit for a Temperature Change from 55 Deg. Fahr. to 109 Deg. Fahr.

range of volumes handled by this program system. For example, in a 1000-mile circuit for the condition where the power output from each repeater is one milliwatt (corresponding roughly to the average power when the program volume is maximum), the non-linear distortion that occurs in the loading causes an increase in the over-all transmission loss of the circuit of only

7. W. J. Shackelton and I. G. Barber, *Compressed Powdered Permalloy—Manufacture and Magnetic Properties*, A. I. E. E. Trans., Vol. 47, April 1928, p. 429.

one db. at 8000 cycles, as compared to the loss for negligibly small power. At 1000 cycles, the loss increment for the same comparison is 0.13 db. The harmonic production in the coils is another measure of their excellence with respect to non-linear distortion. For a 400-cycle line current of 1 milliampere, the ratio of the third harmonic e. m. f. generated in an individual loading coil to the fundamental e. m. f. is equivalent to a loss of 80 db. The current magnitude above assumed corresponds approximately to the maximum repeater output (single-frequency basis) of 1 milliwatt; the

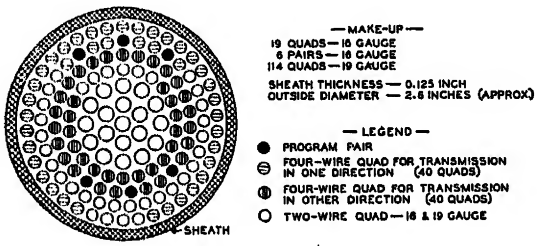

Fig. 7—Cross Section of Typical Full Sized Cable

average current that flows in the loading coils is very much smaller due to the smaller average repeater output and to line attenuation. In this connection, it is to be noted that the third harmonic voltage varies with the square of the magnitude of the fundamental current, and directly with frequency. The higher harmonics are, of course, much lower in magnitude than the third harmonic.

For the purpose of minimizing crosstalk, the loading coils are shielded individually by placing each in a metal container. In addition, the leads to the coils in

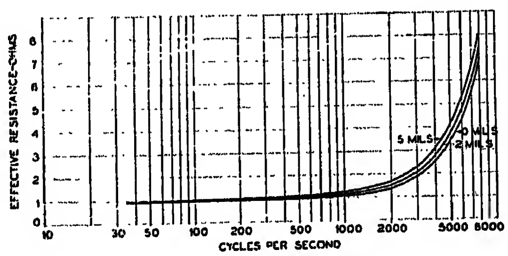

Fig. 8—Effective Resistance of 22 Millihenry Loading Coils Used on Program Transmission Circuits in Toll Cables

the stub cable and within the coil case are cabled in individually shielded quads, the "IN" and "OUT" leads of a loading coil being in the same shielded quad. As a result of these precautions, the crosstalk between the loading coils is practically negligible. Even at the highest frequencies involved in program transmission, the crosstalk is only of the order of two crosstalk units, corresponding to an attenuation of about 114 db.

The shielded program circuit coils required on a given cable are potted separately from the loading coils used on the telephone message circuits. These cases are of welded steel construction. A photograph of a 6-coil case for underground use is shown in Fig. 9. The underground type of case has a special protective coating supplemented by a wrapping of heavy paper.

Amplifiers. Fig. 10 is a schematic of the amplifier circuit as used at non-regulating repeater stations. (At regulating stations an automatic transmission adjustment stage is added, which will be described later.) Front and rear views of the amplifier, which is designed for relay-rack mounting in accordance with present-day telephone practise, are shown in Figs. 11 and 12. The lower panel is the amplifier, the upper the transmission adjustment stage, which will be treated later.

In the regular amplifier a standard Western Electric 102-F tube is used in the first stage and a 101-F tube in the second. The amplifier uses resistance coupling and the various coils which affect the transmission performance have very high inductance so as to give the device very uniform transmission performance at

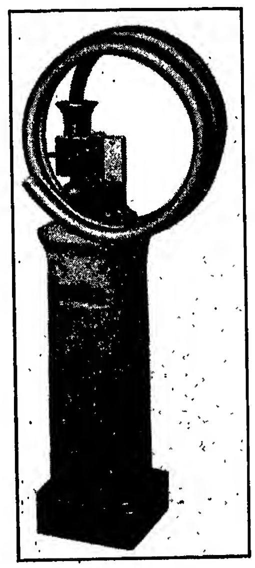

Fig. 9—Six-Coil Underground Loading Case for Cable Program Circuits

different frequencies. The use of permalloy for the cores of these coils makes it possible to obtain the necessary high inductance without going to unreasonable coil dimensions. The gain is controlled by 5 db. and 10 db. artificial lines in the input circuit with a slide-wire potentiometer for the fine adjustments. Resistances in the grid circuit of the second tube allow an adjustment of the gain at high frequencies. Increasing the resistance causes a decrease in gain at these frequencies. The grid potential of the tubes is obtained from voltage drop in the filament circuit. The condenser in the grid circuit with its associated resistance serves to keep noise which may be present in the filament circuit from entering the grid circuit.

The ideal amplifier should give a constant gain for all frequencies over the band to be transmitted regardless of variations in magnitude of current. No extraneous frequencies should appear in the output and all the

frequencies in the band should be transmitted from input to output with equal velocity. With an average spacing of 50 mi. for the repeaters, 40 of these are required on a circuit 2000 mi. long so that obtaining proper performance allows only very small departures of the individual repeaters from the ideal characteristics.

With respect to equality of gain at different frequen-

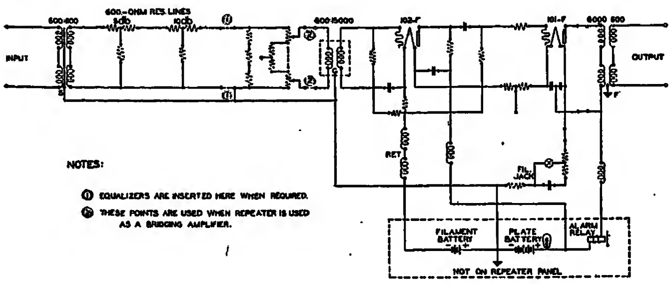

FIG. 10—SCHEMATIC OF NON-REGULATING REPEATER FOR CABLE PROGRAM SYSTEM

cies, if the top and bottom frequencies of the band transmitted over a 2000-mi. circuit are not to drop more than, say, 2 db., below frequencies in the middle of the band, each amplifier is permitted to be only 0.05 db. down at the edges of the band. (This corresponds to a power difference of one per cent.) By the use of resistance coupling and high mutual inductance

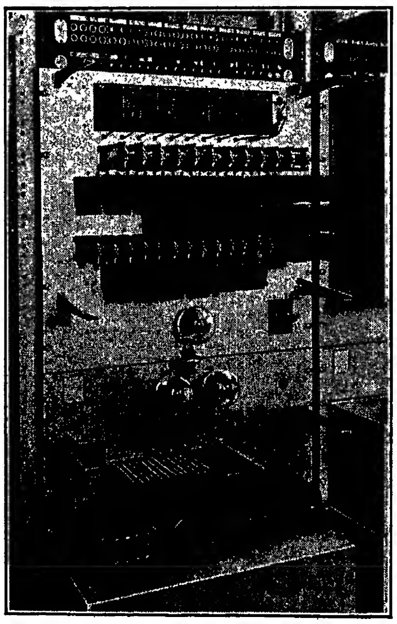

FIG. 11—FRONT VIEW OF PROGRAM AMPLIFIER AND ASSOCIATED REGULATING STAGE. (CAN COVERS REMOVED)

transformers throughout, the amplifiers developed for this system have been given the characteristics shown in Fig. 13. It will be observed that between 100 and 10,000 cycles the gain differences are less than 0.05 db. while at 35 cycles the gain is only 0.2 db. below the gain at 1000 cycles.

With respect to departure of the amplifier from linearity, the effects produced are largely caused by the vacuum tubes. Very little of such distortion is introduced by the amplifier coils. Measurements on one of these amplifiers have shown that with a single frequency output of one milliwatt, which is about the average power corresponding to the maximum program volume, the second harmonics are about 50 db. weaker than the fundamental, *i. e.*, differ in power from the fundamental in the ratio 1 to 100,000. Other harmonics are lower in magnitude.

Non-linearity in the amplifier also manifests itself by change in gain with current strength. In this amplifier a variation in load from one milliwatt to a much weaker load causes a change in gain of only about 0.01 db., while a variation in load from 60 milliwatts to 6 milliwatts causes a change in gain of about 0.4 db.

The input and output coils in the amplifier and, in

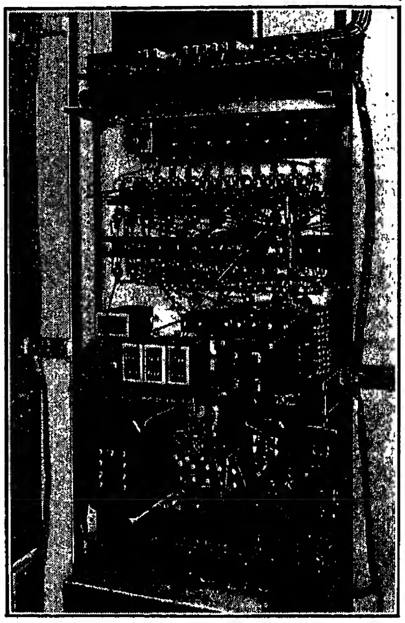

FIG. 12—REAR VIEW OF PROGRAM AMPLIFIER AND ASSOCIATED REGULATING STAGE. (CAN COVERS REMOVED)

the case of the regulating repeater, the retardation coil also, tend to delay the transmission of low-frequency currents more than those of high frequency; an action which is due to the inductance of these coils shunting the circuit. As this reactance becomes less at the lower frequencies, the delay becomes greater. It can be reduced by increasing the values of shunting inductances. It is largely to reduce this effect that permalloy core coils of extremely high inductance are used, as noted above. The condensers appearing in series also cause delay at low frequencies and must be given capacity sufficiently great to keep the delay within proper limits. Inductance in series or capacity in shunt will also result in delay at the high-frequency end. However, in the frequency range covered by these amplifiers there is no difficulty in keeping this delay small enough to be negligible.

The delay characteristic of one of these amplifiers is

shown in Fig. 14. With 40 amplifiers in tandem, the over-all delay at 35 cycles is 75 milliseconds greater than at 1000 cycles, while there is no appreciable difference between the delay at 1000 cycles and the delay at higher frequencies.

Attenuation Equalizers. As will be observed from Fig. 4, the transmission loss of the cable circuit varies considerably with frequency. Since the amplifier has a flat gain characteristic, an attenuation equalizer is called for to correct the distortion introduced by the

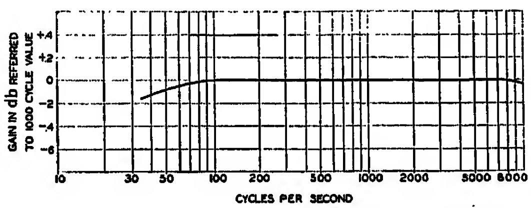

FIG. 13—GAIN-FREQUENCY CHARACTERISTIC OF NON-REGULATING REPEATER WITHOUT LINE EQUALIZER

cable. A diagram of one of these equalizers is shown in Fig. 15. In Fig. 16 is shown the loss introduced by a 50-mi. section of cable at average temperature, the loss introduced by one of these attenuation equalizers and the total loss of line and equalizer with the offsetting gain introduced by the amplifier.

Automatic Device to Overcome Effects of Varying Temperature Transmission Adjusting. As the temperature of the cable changes, its attenuation changes, the amount of the change being different at different frequencies. Referring back to Fig. 6, it is seen that on

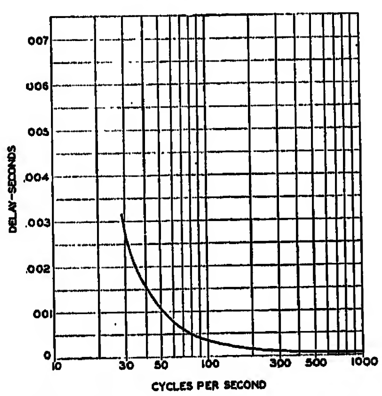

FIG. 14—DELAY-FREQUENCY CHARACTERISTIC OF NON-REGULATING REPEATER

a cable circuit 1000 miles long a temperature change from 55 deg. fahr. to 109 deg. fahr. causes changes in the transmission as follows:

At 100 cycles 18 db. change, power change of 63.

At 1000 cycles 28 db. change, power change of 625.

At 8000 cycles 3 db. change, power change of 2.

When it is appreciated that in an aerial cable a temperature change of 54 deg. fahr. may take place in only a day or two, the importance of compensating for this effect may be appreciated.

In order to compensate for this effect of varying temperature, a regulating stage is added to the amplifiers at the various regulator stations. Fig. 17 shows how the regulating network stage is added to one of the amplifiers and also shows the general nature of the regulating network circuit. Because of the peculiar and complicated way the transmission loss of the cable circuit varies with temperature, a somewhat complicated regulating network is called for. Front and rear views of one of these regulating networks are shown in Figs. 11 and 12, the upper panel being the regulating

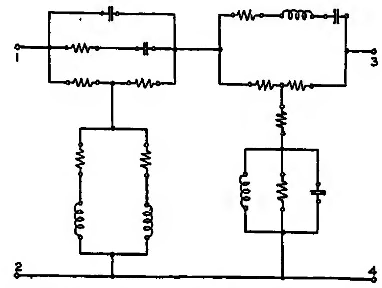

FIG. 15—SCHEMATIC CIRCUIT OF ATTENUATION EQUALIZER

network and the lower the normal amplifier. Fig. 18 shows how the gain characteristic of the amplifier is altered by different steps of the regulating network. This is very closely complementary to the change in cable loss caused by the temperature variations and thus it will be evident that the effects of the temperature changes are largely eliminated.

Delay Equalizers. The velocity of transmission through a loaded cable decreases as the frequency is increased toward the cutoff point of the loading. To

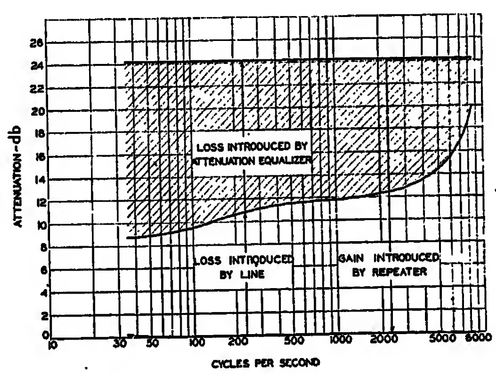

FIG. 16—ATTENUATION-FREQUENCY CHARACTERISTIC OF LINE EQUALIZER AND 50 MILES OF 16-GAGE, B-22 CABLE CIRCUITS

neutralize this effect, delay-equalizing networks are inserted in the circuit which retard the lower frequencies, thus equalizing the velocity of transmission through the combination of cable and networks for all frequencies in the band to be transmitted. Fig. 19 shows the delay characteristic of a section of cable 50 mi. in length, with and without the delay-equalizing networks. The delay is seen to be maintained within $\pm$ 0.05 millisecond of a constant value. A schematic circuit of these networks is shown in Fig. 20. With the greatest length of cable circuits which will be used in this country

for program transmission, this amount of deviation per section is not sufficient to cause objectionable distortion. For a 50-mi. section uncorrected, the delay at 8000 cycles would be 0.9 millisecond greater than at 1000. A description of these delay-equalizing networks with the theory of their performance is being presented in another paper so that a more detailed description is omitted in this paper.

Office Wiring. Owing to the wide frequency range

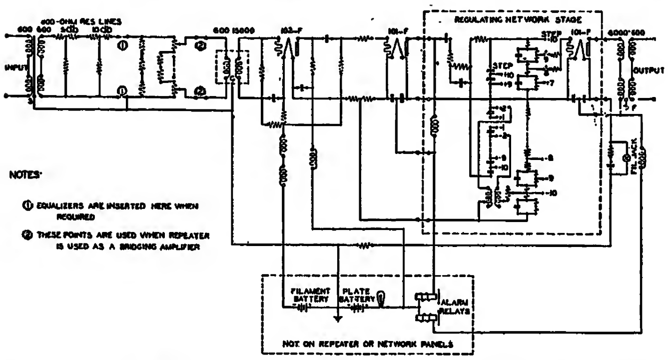

FIG. 17—SCHEMATIC OF REGULATING REPEATER FOR CABLE PROGRAM SYSTEM

transmitted over the circuit, special care must be taken with the office wiring. This is to avoid excessive variations in the losses introduced by this wiring due to changing humidity conditions. A new type of insulated cable is used in which the textile material of the insulating wires has been very thoroughly washed to remove all traces of foreign substances, so that the absorption of moisture with its accompanying increase in loss is greatly reduced.[8] The office cabling is also shortened

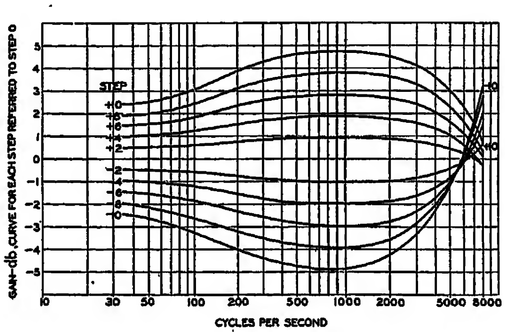

FIG. 18—GAIN-FREQUENCY CHARACTERISTIC OF REGULATING REPEATER WITHOUT LINE EQUALIZER

as much as possible, the outside cable connecting directly to the repeaters without passing through the usual test board. At points in the circuit sensitive to noise interference or crosstalk where the energy level of the transmitted signals is very low, the circuit units are connected by means of shielded pairs. This shield is connected to filament ground, as are also the cases of the various transformers which are insulated from the supporting metallic frame. The unavoidable noise potential existing between the frame and the filament circuit cannot then produce any appreciable disturbance in the circuit.

Over-all Performance of System. A measurement of the transmission loss of the 2200-mi. test length of B-22-N cable circuit gave results as indicated in Fig. 21. It will be observed that over the range from 35

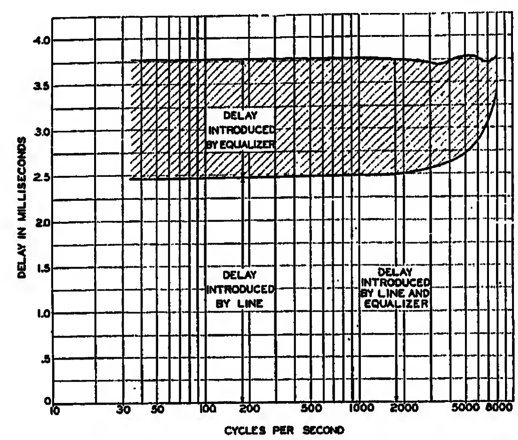

FIG. 19—DELAY-FREQUENCY CHARACTERISTIC OF 50 MILES 16-GAGE, B-22 CABLE WITH AND WITHOUT DELAY EQUALIZER

cycles to 8000 cycles the transmission loss was practically the same at all frequencies, departing only about $\pm$ 2 db. For comparison, another curve (*C*) is given on the same drawing showing the transmission characteristic which would have been obtained if distortionless amplification had simply been added to the line with no attenuation equalizers.

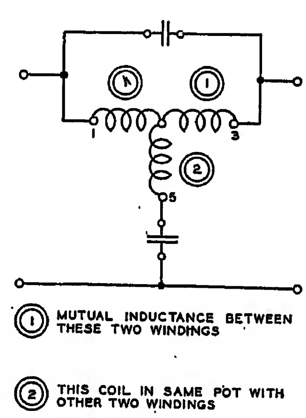

FIG. 20—SCHEMATIC CIRCUIT OF SECTION OF DELAY EQUALIZER

Note: For a 50-mile equalizer, three kinds of sections are used which vary in the resonant frequency and in the sharpness of resonance. The first three sections are of one kind, the fourth is of another, and the last seven are of the third kind

The delay-frequency characteristics of the 2200-mi. test length of B-22 circuit are shown in Fig. 22. Two curves are given, one for the circuit without delay equalizers, the other with delay equalizers.

With respect to non-linear distortion, it was found by test that when the maximum volume was held at about − 5 db. as read on a volume indicator, or about one

8. H. H. Glenn and E. B. Wood, *Purified Textile Insulation for Telephone Central Office Wiring*, A. I. E. E. TRANS., Vol. 48, April 1929, p. 576.

milliwatt of average power, the non-linear distortion became inappreciable. As a matter of fact, occasional bursts up to at least 0 db. were not badly distorted. It may be observed that the − 5 db. volume is about 10 db. less than repeaters of the same nominal capacity and loading coils of similar characteristics handle

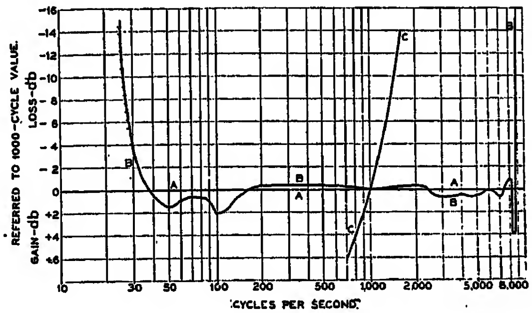

Fig. 21—Transmission-Frequency Characteristics of 2200 Mi. of 16-Gage, B-22 Cable Program Transmission Circuit

Curve A—Ideal characteristic
Curve B—Measured characteristic
Curve C—Line without equalizers

without appreciable distortion under regular message telephone circuit conditions.

The minimum volume which could be transmitted over the cable circuit, which was set by noise and crosstalk picked up by the program circuit, was found to be about − 50 db. at the repeater outputs. This means that the volume range carrying capacity of the circuit was about 45 db., just a little more than the figure 40 db. which was previously mentioned as a reasonable standard for present-day conditions of broadcasting. If short bursts of music are allowed to go up to the zero volume at the repeater outputs, the system can evidently handle about 50 db. volume range.

Using special pickup apparatus and loudspeakers capable of handling practically the whole audible frequency range, tests have been made over the 2200-mi. looped-back circuit in which comparison was made of the transmission with and without the cable included. When an 8000-cycle low-pass filter was included under both conditions it was found that listeners had considerable difficulty in consistently picking a difference. In fact, the ordinary observer could not be relied upon to pick differences consistently even when the 8000-cycle filter was not included.

Conclusion

This development was undertaken to provide a system for obtaining satisfactory channels for the transmission of broadcast programs in the rapidly growing cable network of the Bell Telephone System. The time required to complete such a development and the need for advance planning in the cable plant made it essential that the channels be adequate to render service for a number of years. Improvements in broadcast reproduction may be expected to continue and may very well result in changes in the present frequency allocations to give space for wider bands. The cable system described in this paper was, therefore,

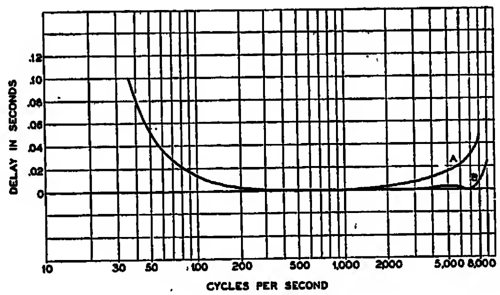

Fig. 22—Delay Characteristics of 2200 Mi. of 16-Gage, B-22 Cable Program Transmission Circuit

	Curve	Delay at 1000 cycles
Circuit without delay equalizers...	A	0.106 sec.
Circuit with delay equalizers......	B	0.168 sec.

developed to possess transmission characteristics superior to present-day radio systems, the margin anticipating improvements which may take place in the future.

Acknowledgment

The authors gratefully acknowledge the assistance of many of their associates in the preparation of this paper, particularly that of Mr. H. S. Hamilton.

The Transmission Characteristics of Open-Wire Telephone Lines

BY E. I. GREEN[1]

Associate, A. I. E. E.

Synopsis.—Values of the primary transmission constants R, L, G, and C for open-wire telephone lines are presented, and the factors which affect these constants in practise are discussed. Consideration is then given to the constants which are of principal interest in telephone work, namely, the attenuation, the characteristic impedance, the phase constant, and the velocity of propagation. Data regarding these characteristics are given for the frequency range from 0 to 50,000 cycles.

INTRODUCTION

NEARLY 3,000,000 miles of open wire are now furnishing toll service in the Bell System, and this total is increasing at a rate of more than 100,000 miles a year. Hence, the subject of the transmission characteristics of open-wire circuits, in addition to being of considerable natural interest, is of no little importance in many branches of telephone work. In the design of apparatus to be associated with the open-wire circuits as well as in the engineering and maintenance of the facilities derived from them, a knowledge of these transmission characteristics is indispensable.

The problem of determining the characteristics of the open-wire circuits has, of course, been coexistent with the circuits themselves, and hence dates back to the beginnings of telephony. Of late years, however, there has been a very decided change in the nature and scope of the problem. This has resulted from many factors, particularly (a) the extensive application of carrier telephone and telegraph systems[2] and (b) the constantly increasing length of the long distance circuits. The first of these factors has extended the transmission range upward from about 3000 cycles to about 30,000 cycles, and may well extend it higher in the future. The second, in combination with the higher standards which are now applied in long distance transmission, has required greater accuracy in the data, emphasizing especially the importance of time and space variations in the characteristics. Also, recent changes in the construction of open-wire lines (to be described later) have necessitated substantial additions to the data.

There will be studied in this paper those inherent characteristics of open-wire lines which are used most frequently in telephone transmission work. These characteristics are: first, the attenuation, second, the impedance, and third, the phase characteristic, with which must be coupled its near relative, the velocity of propagation. The range of frequencies to be covered is fixed on the one hand by the d-c. telegraph systems, as well as by the program transmission circuits, whose lower frequencies extend to 100 cycles or less, and on the other hand by the carrier telephone and telegraph systems, which make the range up to about 50,000 cycles of interest.

LINE CONSTRUCTION ARRANGEMENTS

In order to study the characteristics of open-wire lines it is necessary to know something of the constructional arrangements which are employed. The conductors most commonly used for the open-wire

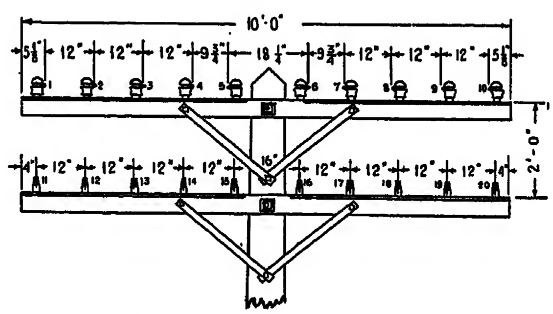

FIG. 1—CONFIGURATION OF AN OPEN-WIRE LINE WITH 12-IN. NON-POLE PAIRS

telephone lines of the Bell System are of 165-mil (No. 8 B. W. G.), 128-mil (No. 10 N. B. S. G.), and 104-mil (No. 12 N. B. S. G.) hard-drawn copper. These are the conductors usually employed for carrier systems. Other gages of copper, as well as a small amount of iron or steel wire, are used to some extent for voice-frequency and d-c. telegraph transmission only.

The wires of the lead (as an open-wire line is frequently designated in telephone parlance) are strung on poles, the normal spacing and numbering of wires being generally as shown in Fig. 1. Starting at the left end of the crossarm, the adjacent horizontal wires are grouped in pairs, wires 1 and 2 comprising one pair, 3 and 4 another, etc. The characteristics of the pairs are of primary interest. Phantom circuits, which are derived from two pairs or side circuits, will be discussed later. The two wires of each pole pair (that is, a pair which bestrides the pole) are about 18 in. apart, and those of each non-pole pair 12 in. apart.

1. Development and Research Dept., American Tel. & Tel. Co., New York, N. Y.

2. *Carrier Systems on Long Distance Telephone Lines*, by H. A. Affel, C. S. Demarest, and C. W. Green, A. I. E. E. TRANS., Vol. 47, 1928, pp. 1360-1386. *Bell System Tech. Jl.*, Vol. VII, No. 3, July 1928, pp. 564-629.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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There has recently come into vogue a different arrangement of wires which is designed to reduce the coupling between circuits and thus permit a maximum use of carrier facilities. This arrangement is portrayed in Fig. 2. In this newer configuration the separation between the wires of each non-pole pair is reduced to 8 in., and the horizontal separation between pairs is widened to 16 in.

The ordinary spacing between poles on open-wire toll lines is 132 ft., corresponding to a total of 40 poles

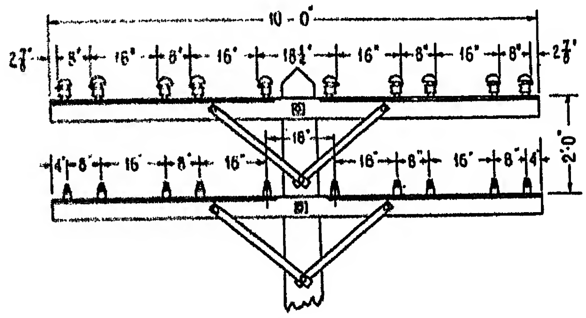

FIG. 2—CONFIGURATION OF AN OPEN-WIRE LINE WITH 8-IN. NON-POLE PAIRS

per mile. Where additional strength is required, the number of poles per mile may be as high as 50, while outside of the heavy sleet area it may be as low as 30.

The types of insulators employed on open-wire lines will be discussed under the heading of leakage conductance.

Two methods of transposing the wires are in current use. In the older of these, which is illustrated in Fig. 3, the wires are brought at the transposition pole to a "drop bracket." The transposition is accomplished

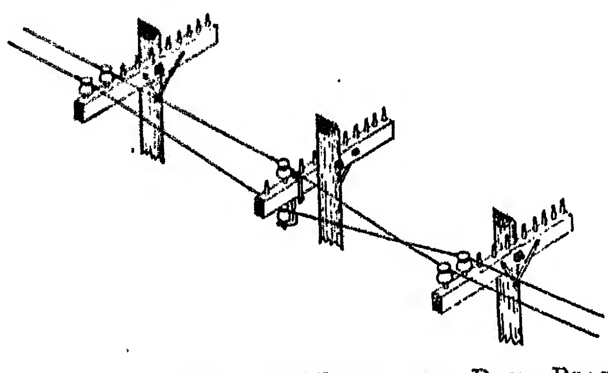

FIG. 3—TRANSPOSITION OF WIRES WITH DROP BRACKET

over a total distance of two spans by gradually rotating the plane of the wires through 180 deg. It will be seen that the wire configuration is abnormal throughout the two spans. In the newer method, the wires are crossed practically at a point. This may be done by means of two brackets known as "break irons," as illustrated in Fig. 4, or by means of a single bracket. The "point" transpositions preserve the nominal spacing between wires and thus avoid the irregularities in spacing which occur when drop bracket or "rolling" transpositions are used. With the point transpositions, however, two pairs of insulators are required at each transposition point as compared with a single pair of insulators at a non-transposition point. This results in an increase in the total number of insulators and in variations in the number of insulators on different pairs because of the different number of transpositions employed.

PRIMARY CONSTANTS

It should be noted here and now that the phenomena of line transmission are the same throughout all of the frequency range under consideration. Transmission over wires at high frequencies is accomplished in precisely the same manner as transmission at low frequencies, the wires acting as the guiding medium for the energy in both cases, and the same theory may be applied to both.

A review of the well-known theory for the propagation of alternating currents over wires will show that the line characteristics in which we are interested are dependent upon the four quantities known as the pri-

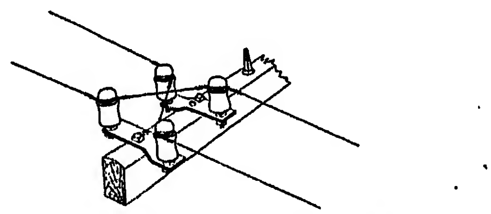

FIG. 4—"POINT" TRANSPOSITION ON BREAK IRONS

mary constants of the circuit. These are as follows:

R = Series resistance in ohms per mile.
L = Series inductance in henrys per mile.
C = Shunt capacitance in farads per mile.
G = Shunt leakage conductance in ohms per mile.

These quantities may be stated per mile of wire or per mile of circuit. In this paper all values will be per mile of circuit, or, as it is commonly expressed, per loop mile.

Unfortunately the constants R, L, G, and C are by no means constant in practise. Indeed there could scarcely be a more fickle set of quantities. They are subject to change by a great variety of factors, of which the most important is, of course, the frequency. Hence it is evident that in order to determine the practical values of the attenuation, impedance, and velocity for open-wire circuits, we shall have to examine the behavior of the primary constants, R, L, G, and C.

RESISTANCE

First in the list of primary constants is generally named the conductor resistance. The method of computing the d-c. resistance is well known and requires no explanation here. In such computations it is assumed that the current density is uniform throughout the cross-section of the conductor. With alternating current, however, the familiar phenomenon of skin effect tends to produce a non-uniform current

distribution, and hence to increase the resistance. If the two wires of a circuit are close together, the effective a-c. resistance of each wire is likewise increased by the presence of the parallel conductor, due to what is known as proximity effect. In cable conductors, especially when used for carrier frequencies, proximity effect is very important, but it is negligible in open-wire circuits because of the large separation between wires.

The method of determining the skin effect resistance of round wires is presented in various publications, and the theoretical results have been experimentally confirmed on numerous occasions.[3] Values of the a-c. resistance of 165-, 128-, and 104-mil copper pairs at 20 deg. cent., (68 deg. fahr.) determined in accordance with skin effect theory, are plotted in Fig. 5. It will be noted that the increase in resistance due to skin effect is small in the voice range, but rather astoundingly large in the carrier range, amounting at the higher frequencies to from 200 to nearly 400 per cent.

Experimental evaluations of open-wire resistance are in extremely close agreement with the values given in Fig. 5.[4] For old wires, however, the resistance may be somewhat higher than these values. This is because of the presence of contact resistance in the twisted

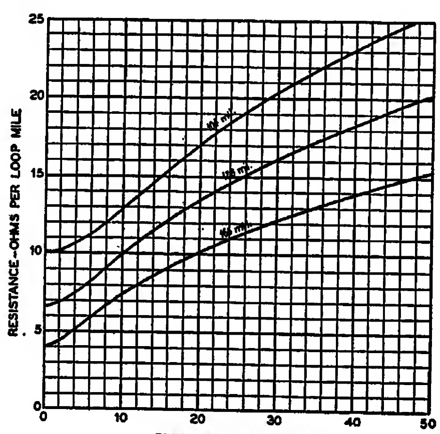

Fig. 5—A-C. Resistance of Open-Wire Pairs at 20 Deg. Cent. (68 Deg. Fahr.)

sleeve joints in the wires and also perhaps because of an actual decrease in the conductor diameter occasioned by corrosion. The increase in the d-c. resistance of old wires due to these causes may be as much as 5 per cent. The corresponding percentage of increase in the a-c. resistance will, of course, be much smaller.

The d-c. resistance of a copper wire varies with temperature according to the familiar formula:

$$R_0 = R_{01}\,[1 + \alpha_1\,(t - t_1)] \tag{1}$$

where R_0 and R_{01} represent the d-c. resistance at temperatures t deg. cent. and t_1 deg. cent. respectively, and α_1 is the d-c. temperature coefficient of resistance of copper at t_1 deg. cent. At a temperature of 20 deg. cent. the value of α_1 is generally taken as 0.00393.

Similarly, the a-c. resistance R of a copper wire at a temperature t may be represented as follows:

$$R = R_1\,[1 + A_1\,(t - t_1)] \tag{2}$$

where

R_1 = a-c. resistance at temperature t_1 deg. cent.

$A_1 = \dfrac{1}{R_1}\,\dfrac{d\,R}{d\,t}$ = a-c. temperature coefficient of resistance of copper at t_1 deg. cent.

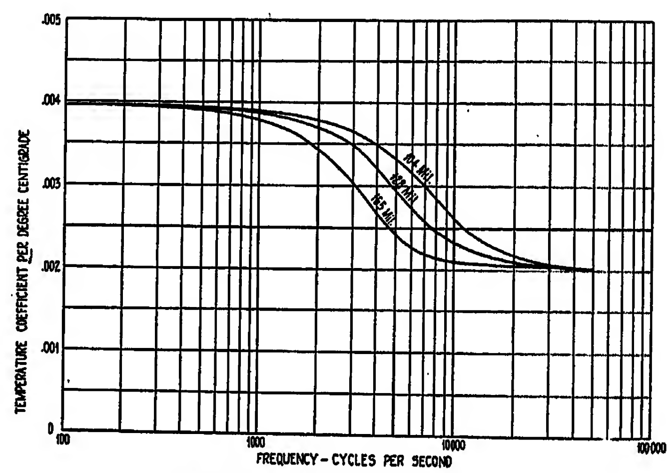

Fig. 6—A-C. Temperature Coefficient of Resistance for Open-Wire Pairs at 20 Deg. Cent.

Now the skin effect resistance ratio depends upon the magnitude of the d-c. resistance, being smaller the larger the resistance. Hence, a given change in temperature which changes the d-c. resistance produces a change in the opposite direction in the skin effect resistance ratio, so that the percentage change in the a-c. resistance is less than the percentage change in the d-c. resistance. In other words, A_1 is less than α_1. As illustrated in Fig. 6, the a-c. temperature coefficient of resistance for open-wire pairs, starting at the d-c. value α_1, straightway decreases as the frequency is increased, and at high frequencies approaches a value of $\dfrac{\alpha_1}{2}$. An explanation for this asymptotic value is presented in Appendix I.

The temperature assumed by the conductors of open-wire lines depends of course, upon the weather conditions which prevail in different sections of the country. In order to obtain information on this sub-

3. "Wave Propagation Over Parallel Wires—The Proximity Effect," J. R. Carson, *Phil. Mag.*, Vol. 41, April 1921, pp. 607-633; *Experimental Researches on Skin Effect in Conductors*, A. E. Kennelly, F. A. Laws, and P. H. Pierce, A. I. E. E. Trans., Vol. 34, Part 2, 1915, pp. 1953-2021, and "Skin Effect Resistance Measurements of Conductors at Radio Frequencies," A. E. Kennelly and H. A. Affel, *I. R. E. Proc.*, Vol. 4, No. 6, Dec. 1916, pp. 523-574.

4. The value of R, and also that of the other primary constants, may be determined directly from open and short-circuit impedance measurements on a line short enough to avoid propagation effects. A longer line may be used instead, in which case it is necessary to correct for such effects.

ject, a study has been made of the Weather Bureau records for a number of representative cities in various parts of the country. The chief interest naturally centers in the extreme temperatures reached by the wires. It appears that on the average the air temperature will not drop below about − 20 deg. cent. (− 4 deg. fahr.) on more than about 10 days per year in the colder sections of the country, while a limiting temperature of about 35 deg. cent. (95 deg. fahr.) will not be exceeded on more than about 10 days per year in the warmer sections of the country. Because of imperfect radiation, the temperature of a wire in the sun will ordinarily exceed the temperature of the surrounding air by a small amount. A few tests have indicated that for open wires the increase over the air temperature on a warm day is not more than 5 deg. cent. Temperatures of − 20 deg. cent. (− 4 deg. fahr.) and 40 deg. cent. (104 deg. fahr.), therefore, appear to be representative values for the limiting temperatures assumed by open-wire lines. Reference to Equation (1) shows that this range of temperature gives possible variations in the d-c. resistance of 16 per cent below and 8 per cent above the value for 20 deg. cent.

The total annual change in resistance at any one place will, of course, be less than the sum of the above changes. In the Middle West, however, where the weather variations are much greater than in other parts of the country, the total annual change in d-c. resistance may be as much as 20 per cent. This section of the country has also the greatest diurnal range of temperature, giving a d-c. resistance variation of as much as 8 per cent.

Inductance

The inductance of a circuit formed of two parallel wires whose distance between centers is negligible compared with their length is

$$L = 0.64374 \left[2.3026 \log_{10} \frac{2D}{d} + \mu\,\delta \right] \times 10^{-3} \text{ henrys per loop mile} \qquad (3)$$

where the diameter of each wire d, and the distance between their centers D, are expressed in the same units, where μ is the permeability, and δ is a factor depending on the frequency.

The tendency of alternating currents to concentrate on the surface of a wire evidently reduces the magnetic flux within the wire and decreases the internal inductance of the wire. In Equation (3) the internal inductance is represented by the factor $\mu\,\delta$. At low frequencies, for which the current is uniformly distributed across the cross-section of the wire, the value of δ is 0.25. For very high frequencies there is practically no magnetic flux within the wire, and the value of δ is zero. Between these frequency limits the value of δ is determined with the aid of skin effect formulas or tables.[5] For the wire diameters and spacings employed on open-wire lines the change in the total inductance due to skin effect is relatively small.

It is assumed in Equation (3) that the two wires are suspended in space or at a considerable distance from the ground and from other wires. In practise, the presence of other wires probably has some effect on the inductance, but for well transposed lines this effect is negligibly small.

The inductance at different frequencies of 165-, 128-, and 104-mil copper pairs having various spacings between wires is shown in the following table.

Frequency cycles per second	Inductance of open-wire pairs—henrys per loop mile								
	165-mil			128-mil			104-mil		
	8-in.	12-in.	18.25-in.	8-in.	12-in.	18.25-in.	8-in.	12-in.	18.25-in.
0	0.00311	0.00337	0.00364	0.00327	0.00353	0.00380	0.00340	0.00366	0.00393
1,000	0.00311	0.00337	0.00364	0.00327	0.00353	0.00380	0.00340	0.00366	0.00393
10,000	0.00305	0.00331	0.00358	0.00323	0.00349	0.00376	0.00338	0.00364	0.00391
25,000	0.00301	0 00327	0.00354	0.00319	0.00345	0.00372	0.00334	0.00360	0.00387
50,000	0.00299	0.00325	0.00352	0.00317	0.00343	0.00370	0.00331	0.00357	0.00384
Infinite	0 00295	0 00321	0.00348	0.00311	0.00337	0.00364	0.00324	0.00350	0.00377

As will be seen from Equation (3), the inductance varies with the logarithm of the separation between wires. In the table the values of inductance are shown for pole pairs, which have a separation between wire centers of about 18.25 inches, and for non-pole pairs having wire separations of 12 and 8 inches. The values of inductance given in the table have been closely checked by measurements on open-wire pairs.

Capacitance

The capacitance of two parallel wires in space with a distance between centers which is negligible compared with their length is

$$C = \frac{0.019415}{\log_{10} \dfrac{2D}{d}} \times 10^{-6} \text{ farads per loop mile} \qquad (4)$$

It will be noted that the capacitance varies in inverse relation to the separation between wires.

As in Equation (3), it is assumed in this formula that the two wires are suspended in space or at a considerable distance from the ground and from other wires. On an actual line the capacitance of a pair is changed to an appreciable extent by the presence of other wires, and to a slight extent by the capacitance to ground. The true capacitance between the two wires under actual conditions may be derived from the direct capacitances between all wires and the direct capacitances of all wires

5. See, for example, Circular No. 74 of the Bureau of Standards, "Radio Instruments and Measurements."

to ground.[6] The capacitance is not changed to any great extent by skin effect.

The means of insulation and support provided at each pole have an appreciable effect on the capacitance of a pair of wires, especially in wet weather. This is due to the fact that the insulators and, under certain conditions, the pins and parts of the crossarms, act as the dielectric of small condensers which are, in effect, shunted between the line wires. These effects are being discussed in a companion paper.[7] The percentage increase in capacitance due to the insulators varies with different weather conditions and different types of insulators, ranging from about 0.5 to 4 per cent of the capacitance between line wires.

Values of the capacitance of 165-, 128-, and 104-mil pairs in space and on a 40-wire line are given in the following table:

Wire spacing	Capacitance—μf per mile					
	165-mil		128-mil		104-mil	
	In space	On 40-wire line	In space	On 40-wire line	In space	On 40-wire line
8 in.	0.00977	0.00996	0.00926	0.00944	0.00888	0.00905
12 in.	0.00898	0.00915	0.00855	0.00871	0.00822	0.00837
18.25 in.	0.00828	0.00863	0.00791	0.00825	0.00763	0.00797

As before, values are given for pairs having wire separations of 8, 12, and 18.25 in. These values include an allowance for the dry weather capacitance of the insulators. The difference between the values in space and on a 40-wire line indicates the importance of the effect of the other wires, the insulators, etc., upon the capacitance. The capacitance values given in the table are fairly representative of the values that will obtain on well transposed lines.

The values of inductance and capacitance which have been given are based on the assumption that the nominal separation between wires is preserved throughout the entire line. This is not the case when drop bracket transpositions are employed. As has been pointed out, the wires are brought closer together at the drop brackets, thereby increasing the capacitance and decreasing the inductance. The amount of the change in inductance and capacitance due to this cause ranges from 1 to 5 per cent for the transposition arrangements designed for carrier system operation.

Leakage Conductance

The leakage conductance per unit length of circuit, which is represented in the transmission formulas by the symbol G, is by far the most erratic of the primary constants. Since it is a momentous factor in the attenuation its investigation has been very actively prosecuted over a considerable period of time.

The determination of the value of G for direct current is quite simple, involving merely a measurement of the actual conductance between wires for a length of circuit short enough to avoid propagation effects. For alternating currents, however, it is customary to employ an equivalent value of G which includes all of the losses suffered by the power transmitted over the pair except the normal $I^2 R$ loss in the wires themselves. This inclusion of numerous little-understood losses in the general term leakage has at times served to insulate the individual losses from analysis. Methods of determining the value of the "equivalent leakage conductance" and of analyzing its component losses are available, however.[8]

The nature and magnitude of the different losses which occur at the insulators are being discussed in detail in a parallel paper.[7] Accordingly, only a brief mention will be made in this paper of the types of insulators which are now in use on the open-wire lines of the Bell System, and of the values of leakage conductance experienced with these different types.

The $D P$ or double-petticoat glass insulator illustrated in Fig. 7 is now standard for use on all important toll circuits, except those equipped with the special carrier insulators discussed below. On a number of older circuits single-petticoat glass insulators, known as toll insulators, (see Fig. 7) and double-petticoat porcelain insulators are still in place.

In view of the numerous and complex sources of leakage loss, it is not surprizing that the leakage conductance for a given pair at a particular frequency varies with changing weather conditions and with the age of the insulators over a very wide range of values. Because of this wide range of variation it is possible to give here only selected leakage values which serve for engineering purposes. Values of the total leakage conductance for open-wire pairs equipped with $D P$ insulators are plotted in Fig. 8. These values are intended to represent the highest values ordinarily obtained on an old circuit which is in a good condition of maintenance. The wet weather values have been so chosen that they should be exceeded on only a few days of the year, while the dry weather values represent the performance that should be expected from any circuit on a clear, dry day.

Particular difficulty is experienced in selecting standard values of d-c. leakage owing to the fact that the range of values encountered in practise is exceedingly great. The measured values depend to a great extent on the degree to which the line is kept free from tree branches, foliage, moss, broken insulators, and other possible sources of leakage. These special

6. See Technical Report No. 54 of the Railroad Commission of the State of California, Joint Committee on Inductive Interference, entitled "Inductive Interference Between Electric Power and Communication Circuits," 1919.

7. "A Study of Telephone Line Insulators," by L. T. Wilson. Presented at the Summer Convention of the A. I. E. E. Toronto, Ont., Canada, June 23-27, 1930.

8. *Methods of Measuring the Insulation of Telephone Lines at High Frequencies*, by E. I. Green, A. I. E. E. Trans., Vol. 46, 1927, pp. 514-519.

sources of loss, of course, represent a much smaller part of the total leakage losses at carrier frequencies.

The standard values of leakage conductance are derived for a line having 40 pairs of insulators per mile. Where the number of insulators differs greatly from this figure, it is necessary to correct the leakage values accordingly. Differences in the number of insulators per mile result from the use of different types and numbers of transpositions, different pole spans, double crossarm construction, etc.

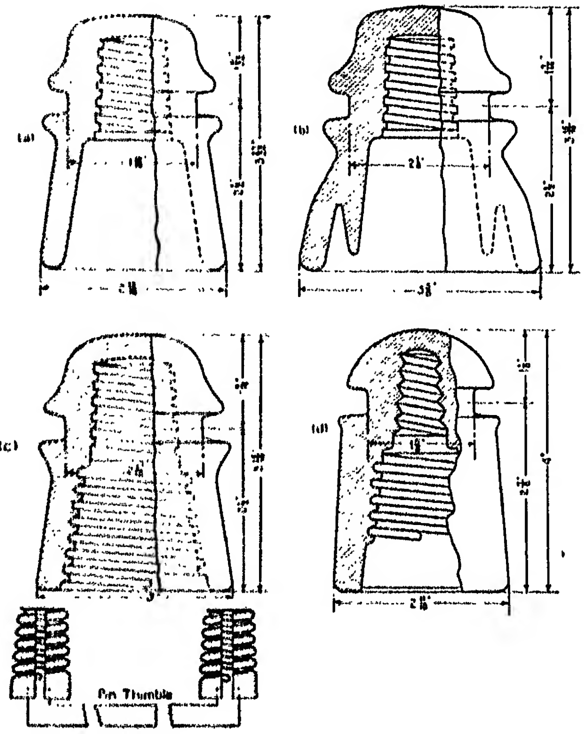

FIG. 7—TYPES OF INSULATORS EMPLOYED IN THE BELL SYSTEM

a. Toll insulator
b. *D P* insulator
c. *C W* insulator and pin thimble
d. *C S* insulator

Considerable study has been given to methods of reducing the leakage conductance, particularly at carrier frequencies, and two new types of insulators have been developed for this purpose. In these there is used an improved dielectric (borosilicate glass) which has a low power factor and a reasonably low dielectric constant, as well as good chemical stability. Two expedients for eliminating losses in the pins and crossarm are employed. In the *C W* insulators, illustrated in Fig. 7, two metal shells or thimbles are bonded together and placed over the wooden pins. In the *C S* insulator, also shown in Fig. 7, steel pins are employed and the two steel pins of the pair are bonded together. In the past few years *C S* insulators have been applied to the open-wire lines of the Bell System in increasingly large numbers.

With these two types of insulators a substantial reduction in the total leakage conductance is brought about. The best available figures for the limiting values of leakage conductance for these types are shown in Fig. 8. A further advantage obtained through the application of the new insulators is that of stabilizing the attenuation at carrier frequencies. Experience has indicated that the *C S* and *C W* insulators reduce the daily leakage (and attenuation) variations due to change in weather conditions to about one-third and one-half, respectively, of their value for *D P* insulators. This degree of stabilization is not indicated by the differences between the dry and wet weather leakage values shown in the figure, but it must be recalled that these values represent extreme conditions, while the stabilization referred to above is for average conditions.

ATTENUATION

The attenuation constant is the real part α of the propagation constant γ as given in the familiar formula

$$\gamma = \alpha + j\,\beta = \sqrt{(R + j\,L\,\omega)\;(G + j\,C\,\omega)} \qquad (5)$$

The attenuation constant is also given by the following expression

$$\alpha^2 = 1/2\left[\sqrt{(R^2+L^2\,\omega^2)\;(G^2+C^2\,\omega^2)} - (L\,C\,\omega^2 - R\,G)\right] \qquad (6)$$

Where $L^2\,\omega^2$ is large compared to R^2 and $C^2\,\omega^2$ is large compared to G^2, it can be shown[9] that Equation (6) reduces to

$$\alpha \doteq \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \qquad (7)$$

This formula is very useful for computing the attenuation of open-wire circuits at carrier frequencies, in which case its accuracy is adequate for all practical purposes. It is frequently of value also for quick computations of the approximate attenuation of open-wire circuits in the voice range.

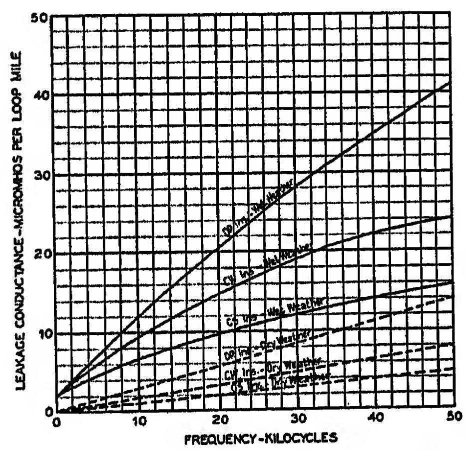

FIG. 8—LEAKAGE CONDUCTANCE OF OPEN-WIRE PAIRS EQUIPPED WITH DIFFERENT TYPES OF INSULATORS

The first term of Equation (7) represents the series losses, and is commonly referred to as the "resistance component of attenuation," while the second term represents the shunt losses, and is called the "leakage

9. See "Transmission Circuits for Telephonic Communication," by K. S. Johnson, N. Y., Van Nostrand, 1927.

component of attenuation." It will be observed that the resistance component of attenuation varies inversely with the quantity $\sqrt{\dfrac{L}{C}}$, while the leakage component varies directly with the same quantity. This quantity $\sqrt{\dfrac{L}{C}}$, as will be seen later, represents the nominal characteristic impedance of the circuit.

It is shown in Appendix II that a circuit of fixed resistance and leakage conductance will have minimum attenuation when the ratio of L to C is such as to make the resistance component equal to the leakage component. Because of the variation of the resistance and leakage conductance with frequency, the ratio of L to C which gives minimum attenuation evidently depends upon the frequency. At voice frequencies the resistance component for open-wire circuits is, as a rule, considerably larger than the leakage component, so that it is generally possible to reduce the voice-frequency attenuation by inserting loading coils, which increase the value of L and thus reduce the resistance component at the expense of an increase in the leakage component. The amount of reduction in attenuation obtainable by loading is evidently limited by the value of the leakage component and by the additional resistance which is contributed by the loading coils. For open-wire circuits at carrier frequencies the value of the leakage component of attenuation is quite large in comparison with the resistance component, and coil loading would, in general, be detrimental. At the present time the use of loading on the open-wire circuits of the Bell System has been practically abandoned. Owing to the importance of other factors, especially the line crosstalk, it is ordinarily impracticable to design the open-wire circuits to secure precisely the minimum attenuation at the highest working frequency. In the carrier frequency range, however, the wet weather attenuation of the pairs most commonly used is not materially higher than the theoretical minimum.

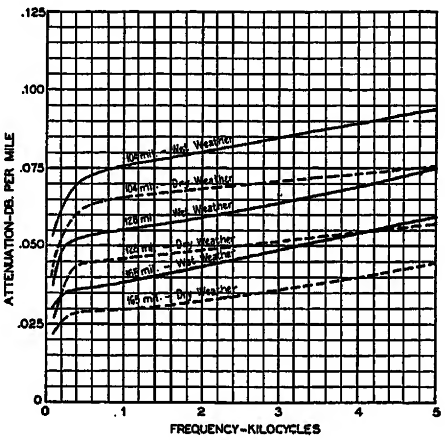

Fig. 9—Voice-Frequency Attenuation of Open-Wire Pairs Equipped with D P Insulators

Values of the attenuation constant of open-wire pairs of different gages when equipped with $D\,P$ insulators are presented in Figs. 9 and 10. The values are plotted in db. per mile.[10]

The attenuation values of Figs. 9 and 10 have been determined for a temperature of 20 deg. cent. (68 deg. fahr.) and for the dry and wet weather values of leakage conductance previously presented. It will be recalled that these values of leakage are derived on the basis of 40 pairs of insulators per mile, and are intended to represent, not average values, but the highest values ordinarily obtained under conditions of dry and wet weather. Systems are ordinarily engineered on the basis of the extreme wet weather attenuation values. When a line runs through the more arid parts of the country, however, advantage is often taken of this fact by making the repeater spans longer than normal.

A comparison of the attenuation values for a 165-mil open-wire pair when equipped with different types of insulators is presented in Fig. 11. For purposes of comparison with the normal values a curve of the attenuation due to resistance only, representing the ideal condition of zero leakage conductance, also is given in Fig. 11.

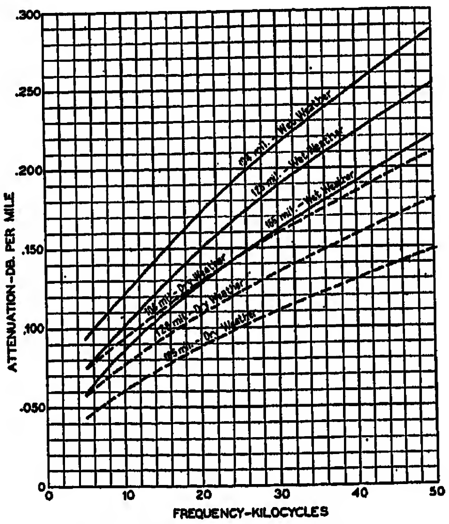

Fig. 10—Carrier Frequency Attenuation of Open-Wire Pairs Equipped with $D.$ $P.$ Insulators

The values of line capacitance employed in determining the attenuation values of Figs. 9, 10, and 11 include an allowance for the average capacitance increase due to the insulators. The attenuation curves shown are strictly applicable to pairs having a wire separation of 12 in., but they are approximately correct for spacings of 8 and 18.25 in.

When the number of pairs of insulators per mile

10. "Decibel—The Name for the Transmission Unit," by W. H. Martin, *Bell System Tech. Jl.*, Vol. VIII, No. 1, January 1929, pp. 1-2.

differs greatly from the standard value of 40, a correction is applied to the attenuation values. Special curves make it possible to obtain this correction conveniently. Curves are also available for correcting the standard attenuation values to take care of changes in temperature.

It should be understood that the attenuation of an open-wire pair varies from time to time over a wide range of values, and therefore it is not to be expected that the values of attenuation measured at any particular time will necessarily coincide with the theoretical

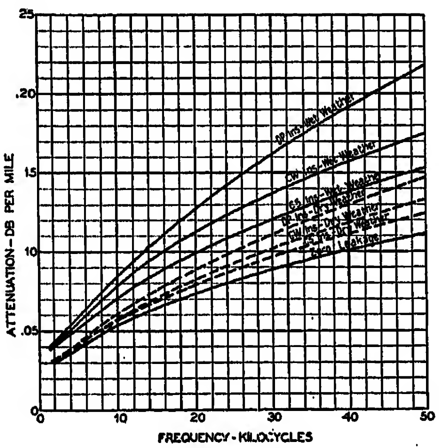

FIG. 11—ATTENUATION OF 165-MIL OPEN-WIRE PAIR FOR VARIOUS CONDITIONS OF INSULATION

values. It should also be understood that the attenuation measured on an actual pair never bears the perfectly smooth relation to frequency which is shown on the standard attenuation curves, but exhibits irregularities varying in magnitude according to the irregularities existing on the line. Thus the curve of attenuation as measured on a very well transposed open-wire pair,[11] which is delineated in Fig. 12, represents about as smooth an attenuation curve as it is possible to obtain on an open-wire circuit. The attenuation values shown on this curve are somewhat lower than the standard values for similar pairs. This is doubtless explained by the fact that the insulators on this particular pair were new, and the further fact that the measurements were made in winter when the temperature was low.

An illustration of the significance of the attenuation data given above may be of interest. One of the longest carrier telephone systems now in service extends from Davenport, Iowa to Sacramento, California, a total distance of about 2100 miles. The highest frequency employed in this system is approximately 28,000 cycles. Using the attenuation values for a 165-mil pair at 28,000 cycles, it appears that the dry weather attenuation for the entire length of this system might be approximately 220 db. or less, and the wet weather attenuation about 330 db. This means that without amplification along the line the ratio of the transmitted power to the received power might vary from 10^{22} to 10^{33}. Since the attenuation of a repeater section is ordinarily limited to from 25 to 40 db. ten repeaters are employed to span the total distance, and in order to compensate for the attenuation variations a gain regulating mechanism known as a pilot channel must be used.

In the preceding illustration it was assumed that the range of variation in attenuation increases in direct proportion to the length of the circuit. Although this may theoretically be possible, it has been found in practise that the attenuation variations during any given period of time increase less rapidly than the circuit length. The reason for this is that augmenting the length of the circuit obviously reduces the likelihood of experiencing extreme wet weather conditions simultaneously over the entire line. A practical example of how the open-wire attenuation varies from time to time is afforded by Fig. 13, which shows the measured attenuation changes on a line 110 miles long during the period of two light rainstorms.

One further point is of interest in connection with the subject of open-wire attenuation. Inductive or conductive coupling between a pair and the other circuits on the line may result in the absorption of energy in these circuits. Fortunately, the losses due to this cause are small on well transposed lines. On inadequately transposed lines, however, this interaction with other circuits, in addition to producing small losses

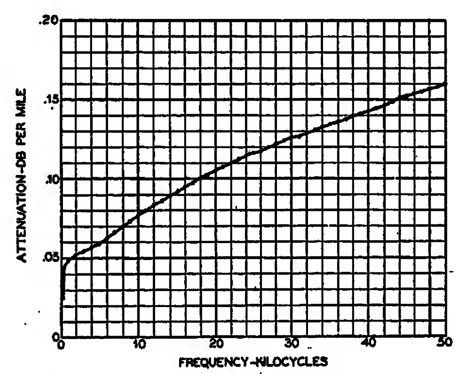

FIG. 12—ATTENUATION MEASURED ON A WELL-TRANSPOSED 128-MIL OPEN-WIRE PAIR WITH 8-IN. SPACING

over a wide range of frequencies, may cause incredibly large losses over a narrow band of frequencies, producing what is known as an "absorption peak" in the attenuation curve. This interesting phenomenon is illustrated in the attenuation curves of Fig. 14, which show how two very pronounced absorption peaks on a line about 300 miles in length were smoothed out by the application of improved transpositions. The magnitude of one of these absorption peaks will be appreciated when it is realized that the received power at the peak

11. Methods of measuring the attenuation, impedance, and crosstalk are discussed in *High-Frequency Measurements of Communication Lines*, by H. A. Affel and J. T. O'Leary, A. I. E. E TRANS., Vol. 46, 1927, pp. 504-513.

frequency is about one two-hundredth of that at the adjacent frequencies.

Impedance

The characteristic impedance is defined by the well-known formula:

$$Z_0 = \sqrt{\frac{R + j L \omega}{G + j C \omega}} \text{ ohms} \qquad (8)$$

It is doubtless unnecessary to explain why this impedance must be matched in the apparatus.

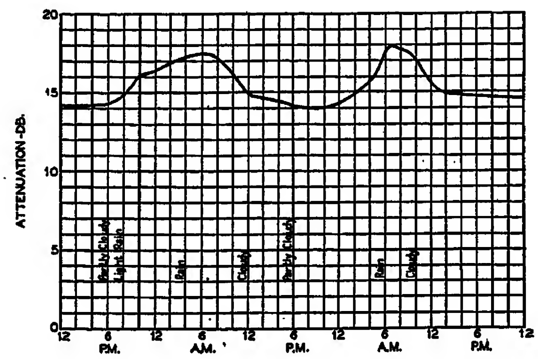

Fig. 13—Measured Variations in the Attenuation of an Open-Wire Pair

When R is small compared to $L\,\omega$ and G is small compared to $C\,\omega$, the value of Z_0 evidently becomes

$$Z_0 \doteq \sqrt{\frac{L}{C}} \qquad (9)$$

This is known as the nominal characteristic impedance.

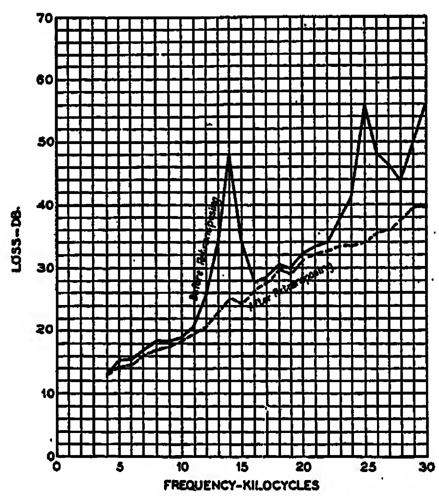

Fig. 14—Absorption Peaks on an Open-Wire Pair

It will be noted that this impedance is a pure resistance. In the carrier range the actual impedance of an open-wire pair is substantially equal to the nominal characteristic impedance.

Values of the characteristic impedance in dry weather of open-wire pairs with 12-inch wire spacing are presented in Fig. 15. These values have been derived from the standard values of inductance, capacity, and leakage conductance and from resistance values at 20 deg. cent. The basis for the impedance value of 600 ohms resistance, which has become almost a tradition in so many phases of telephone work, will be obvious from Fig. 15. The impedance curves for pairs with 8-in. and 18.25-in. spacing are similar to those of Fig. 15, the resistance values for these spacings being about 45 ohms lower, and 40 ohms higher, respectively, than the values shown for 12-in. spacing.

Changes of resistance and leakage conductance due to changing weather conditions have very little effect on the characteristic impedance at frequencies above 1000 cycles. Changes of insulator capacity due to changing weather conditions or the use of different numbers or types of insulators have an appreciable effect on the impedance. Deviations from the normal spacings between wires which result from the use of drop bracket transpositions also have an important effect upon the impedance.

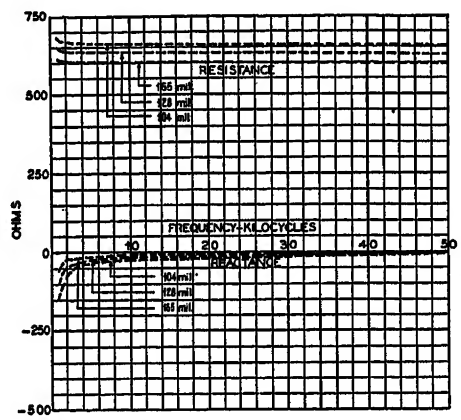

Fig. 15—Carrier-Frequency Impedance of 12-In. Open-Wire Pairs

Like the measured attenuation, the impedance which is measured for an open-wire pair is affected by the presence of line irregularities. Hence, the measured impedance is never a smooth function of frequency, but displays slight irregularities throughout the entire range. This is apparent from Fig. 16, which gives a curve of the impedance measured on a well transposed pair. This curve is in remarkably close accord with the generalized values of impedance, the maximum deviation from the theoretical curve being about 2 per cent.

Like the attenuation, the impedance of an open-wire circuit in a narrow band of frequencies may be radically changed by interaction with adjacent circuits. These large irregularities in the impedance commonly accompany absorption peaks in the attenuation, and are, of course, due to the inadequacy of the line transpositions.

Phase Change and Velocity of Propagation

The imaginary component β of the propagation constant is known as the phase constant because it indicates the change in the phase of the voltage and current in circular radians per unit length of line.

The value of the phase constant is given by

$$\beta^2 = 1/2\,[\sqrt{(R^2+L^2\,\omega^2)\,(G^2+C^2\,\omega^2)}+(L\,C\,\omega^2-R\,G)] \quad (10)$$

If R^2 and G^2 are small compared to $L^2\,\omega^2$ and $C^2\,\omega^2$ it is clear that

$$\beta \doteq \omega\sqrt{L\,C} \text{ radians per mile} \quad (11)$$

For an open-wire pair the value of β is approximately 0.035 radian per mile, or 2 deg. per kilocycle per mile. The latter figure is a convenient one to remember.

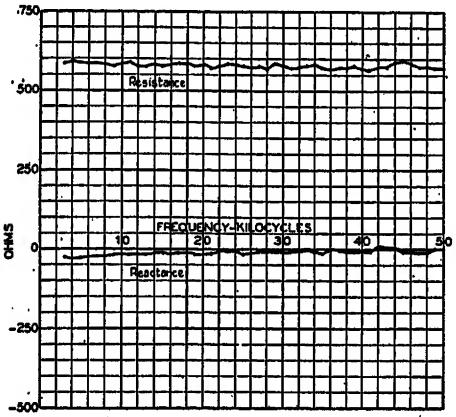

Fig. 16—Impedance Measured on a Well-Transposed 128-Mil Open-Wire Pair with 8-In. Spacing

The constant β also enters into the familiar expression for the velocity of propagation

$$V = \frac{\omega}{\beta} \text{ miles per second} \quad (12)$$

The velocity of propagation on open-wire lines approaches the velocity of light, which is 186,000 miles per second. The velocity is reduced below this value by the increase of capacity due to the presence of the other wires and the insulators, by the internal inductance, and by the presence of resistance and leakage conductance. Values of the velocity of transmission for open-wire pairs are presented in Fig. 17. At frequencies above a few hundred cycles the velocity of transmission is, apart from the effect of line irregularities, practically constant throughout the frequency range.

In the last few years increasing attention has been focused upon the phase characteristic of the open-wire circuit. One of the reasons for this is that different velocities of transmission for different frequency components in a signaling band (which are obtained when the phase shift of the circuit is not a linear function of the frequency) may give rise to what is known as phase distortion, and it may be necessary to correct this distortion by suitable networks.[12,13]

Characteristics of Phantom Circuits

Phantom circuits, which are derived from two pairs or side circuits by transmitting over the wires of one pair in parallel and using the wires of the other pair in parallel as a return, have been employed in the telephone plant for voice-frequency transmission for a number of years. Their use for carrier transmission is limited chiefly by the difficulty of reducing the cross induction with other circuits at high frequencies.

Phantom circuits are generally derived either from horizontally adjacent non-pole pairs or from vertically adjacent pole pairs. Thus wires 1 and 2 are "phantomed" with wires 3 and 4, wires 5 and 6 with wires 15 and 16, etc. In some of the newer transposition arrangements the non-pole pairs are not phantomed, since it has been found that the omission of the phantom permits the operation of a larger number of carrier systems on one line without excessive mutual interference.

The resistance of a phantom circuit is evidently half of the corresponding value for the side circuit.

If the two wires forming one of the sides of the phantom circuit are designated 1 and 2, and the wires

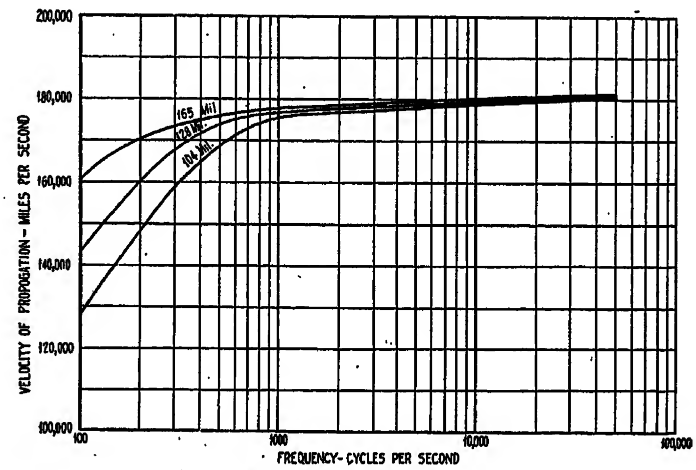

Fig. 17—Velocity of Propagation for Open-Wire Pairs

forming the other side are designated 3 and 4, the inductance of the phantom circuit is

$$L = 0.32187\left[1.1513\log_{10}\frac{4\,D_{13}\,D_{14}\,D_{23}\,D_{24}}{D_{12}\,D_{34}\,d^2}+\mu\,\delta\right]$$

$$\times\,10^{-3} \text{ henrys per loop mile} \quad (13)$$

where D_{13}, D_{23}, etc. represent the spacing between the

12. "Distortion Correction in Electrical Circuits with Constant Resistance Recurrent Networks," by O. J. Zobel, *Bell System Tech. Jl.*, Vol. VII, No. 3, July 1928, pp. 438-534.

13. *Wire Transmission System for Television* by D. K. Gannett and E. I. Green, A. I. E. E. Trans., Vol. 46, 1927 pp. 946-953; (*Bell System Tech. Jl.*,) Vol. VI, No. 4, October, 1927, pp. 616-632.)

wires 1 and 3, 2 and 3, etc., and where d, μ, and δ have the same significance as in Equation (3).

The capacitance of a phantom circuit in space is

$$C = \frac{0.07766 \times 10^{-6}}{\log_{10} \dfrac{4\, D_{13}\, D_{14}\, D_{23}\, D_{24}}{D_{12}\, D_{34}\, d^2}} \text{ farads per loop mile} \quad (14)$$

Equations (13) and (14) are based on the assumption

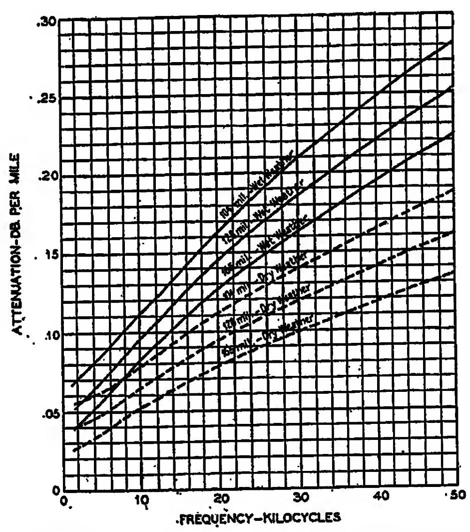

FIG. 18—ATTENUATION OF PHANTOM OPEN-WIRE CIRCUITS

that the phantom circuit is sufficiently well transposed to secure balanced voltages, currents, and charges on the four wires. The capacitance of the phantom circuit is, of course, affected by the capacitances of its component wires to the other wires of the lead and to ground and also by the capacitances of the insulators.

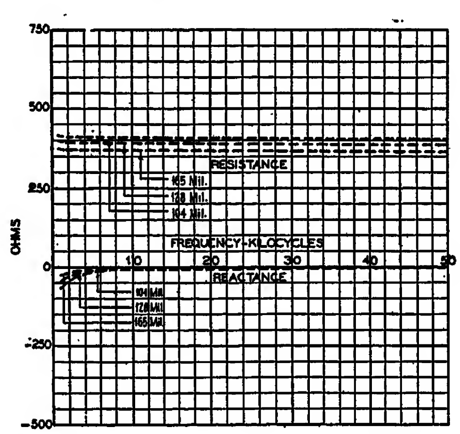

FIG. 19—IMPEDANCE OF PHANTOM OPEN-WIRE CIRCUITS

The losses which contribute to the leakage conductance of phantom circuits are similar to those which have been discussed for side circuits. The ratio of the phantom circuit leakage conductance to that of the side circuit will depend upon the relative magnitudes of these different losses. Varying relations between the different types of losses give a ratio of phantom circuit leakage conductance to side circuit leakage conductance which might conceivably range between the extremes of 1 and 6. For practical engineering purposes, however, the leakage conductance of the phantom circuit is generally assumed to be twice that of the side circuit.

Curves of the attenuation of non-pole pair 12-in. phantom circuits of different gages are depicted in Fig. 18. In most cases the attenuation of the phantom circuit is somewhat less than that of the corresponding side circuit. Frequently, however, the advantage of lower attenuation is under practical conditions more than offset by the large noise and crosstalk effects experienced on the phantom circuits.

Values of the dry weather impedance of 12-in. phantom circuits are presented in Fig. 19. It will be observed that the impedance of a phantom circuit averages about 60 per cent of the impedance of a 12-in. side circuit.

CHARACTERISTICS OF IRON-WIRE CIRCUITS

There now exists on the toll lines of the Bell System

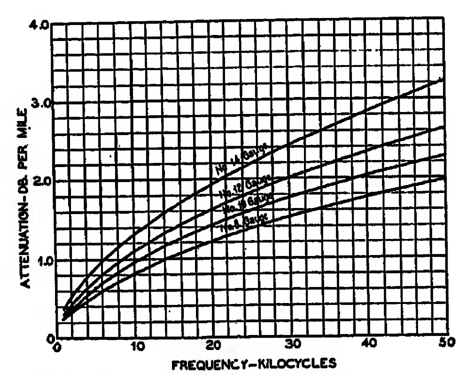

FIG. 20—ATTENUATION OF IRON WIRE CIRCUITS

a small amount of galvanized iron or steel wire. Nos. 12 and 14 B. W. G., with diameters of 109 and 83 mils, respectively, are the gages most commonly found. Steel wire and BB iron wire are both used, the latter being of more frequent occurrence. These iron-wire pairs display such large values of modulation and high-frequency attenuation that they are generally quite unsuitable for carrier transmission.

The skin effect resistance of iron wire may be computed by standard theory, provided that the values of the resistivity ρ and permeability μ are known. The values of ρ for BB iron and steel wire are about 12.8 and 14.8 microhm-centimeters respectively. It will be noted that these values are about seven and eight times the resistivity of copper. For currents of telephonic magnitude at frequencies from about 500 to 50,000 cycles, it has been found that the value of the permeability μ of iron wire of the above sizes ranges from about 110 to 50. Study of the available data indicates that the best average value of μ at 1000 cycles is about 85 and that the effective value decreases with

increasing frequency. Because of the high d-c. resistance and the large skin effect ratio which results from the high permeability, the resistance of iron wire for alternating currents is extremely great.

Except at low frequencies, where the internal inductance of the iron wire is large, the total inductance of an iron-wire circuit is not far different from that of the corresponding copper circuit. The capacitance and leakage conductance of iron-wire circuits are substantially the same as for similar pairs of copper wire.

Typical attenuation curves for several gages of BB iron wire in dry weather are shown in Fig. 20. These curves are based upon experimental results. It will be noted that the attenuation of an iron-wire circuit averages about ten times that of the corresponding copper-wire circuit. It should be understood that the attenuation values for an iron-wire circuit are subject to rather wide variations in practise, particularly because of the effects of corrosion. There is some change in the attenuation of an iron-wire circuit with change in weather conditions, but this is a relatively small percentage. The impedance of an iron-wire circuit has same order of magnitude as the impedance of a similar copper-wire circuit.

Appendix I

Temperature Coefficient of Resistance at High Frequencies

In the skin effect literature cited in the text, it is shown that at high frequencies the a-c. resistance R is

$$R = 0.00979\sqrt{fR_0} \tag{15}$$

where R_0 is given by Equation (6) and f is the frequency. Differentiating with respect to t, and substituting, we find that

$$A_1 = \frac{1}{R_1}\frac{dR}{dt} = \frac{1}{2}\alpha_1\sqrt{\frac{R_{01}}{R_0}} \tag{16}$$

and for ordinary ranges of temperature

$$A_1 = \frac{\alpha_1}{2} \tag{17}$$

Appendix II

Condition for Minimum Attenuation

The attenuation at high frequencies is given by Equation (7). Differentiating this with respect to $\sqrt{\frac{C}{L}}$, and setting the result equal to zero, it is found that the condition for minimum attenuation is

$$\frac{L}{C} = \frac{R}{G} \tag{18}$$

which is another way of saying that

$$\frac{R}{2}\sqrt{\frac{C}{L}} = \frac{G}{2}\sqrt{\frac{L}{C}} \tag{19}$$

so that the resistance and leakage components must be equal in order to have minimum total attenuation.

A Study of Telephone Line Insulators

BY L. T. WILSON*
Non-member

Synopsis.—This paper discusses the major factors contributing to the (total) leakage conductance of telephone line insulators, especially at carrier frequencies up to 50,000 cycles. The influence of both the design and material of the insulators and pins on each factor is discussed and illustrated by test data.

The electrical performance of three different designs is analyzed to illustrate, in a general way, the relative importance of the several factors.

Introduction

To the layman, the long strings of large power insulators suspended from tall steel towers naturally present a more imposing picture than do the small telephone insulators mounted on the crossarms of relatively short wooden poles.

To the engineer, however, these little insulators present problems quite as stimulating and interesting in the telephone field as do the large insulators in the power field.

It is the purpose of this paper first to discuss briefly how some of these interesting problems arose and then to cover in more detail a study of the major phenomena involved in insulator leakage and finally to show how the knowledge gained from that study has helped bring about improved telephone insulators, some of which will be described.

Origin of Problem

For many years the requirements of telephone insulators were relatively easy to meet because the frequency of the currents transmitted did not exceed about 3 kc. and because the leakage of insulators is generally low at such frequencies.

Therefore, the familiar glass insulators such as are shown in Figs. 1 and 2 sufficed, the former design (D. P. type) being employed on the longer circuits and the latter (toll type) or the shorter ones. Indeed they still suffice very generally, especially where only currents of voice frequencies or less are transmitted.

The advent of carrier systems employing higher frequencies ranging from about 3 to 30 kc. changed the insulator requirements substantially. At first these systems were few in number and relatively short in length and the insulator problem accordingly less important.

The rapid growth of carrier systems during the past decade,[1] the longer circuits to which they have been applied, and improved standards of long-distance transmission have all been factors in increasing the requirements imposed upon the insulator and in correspondingly augmenting the importance of the problem.

It may now be remarked that the problem has been mainly one of securing economical insulators giving improved performance at these higher frequencies. In addition the low frequency performance of new designs had to be maintained substantially as good as that of the old designs.

Leakage Phenomena

This study has been confined almost entirely to the pin type of insulator.

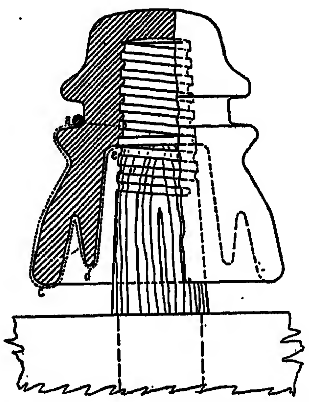

Fig. 1—Standard D. P. Insulator and Standard Wood Pin

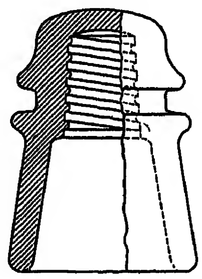

Fig. 2—Standard Toll Insulator

When an alternating potential exists between a pair of wires at the point where those wires are supported by insulators, a current flows from the one wire to the other. This current may be resolved into two components, one in phase with the potential and one in phase quadrature leading the potential.

This in-phase component which, of course, represents an energy loss is the one of chief interest here and in using the word leakage we refer to this component, or more accurately to its equivalent conductance.

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1. See *Carrier Systems on Long Distance Telephone Lines*, H. A. Affel, C. S. Demarest, and C. W. Green, A. I. E. E. Trans., Vol. 47, 1928, p. 1360-1386.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

Of course, both components in flowing through the resistance of the line conductors produce energy losses but these are so small as to be omitted here. Except these, all other energy losses which occur due to the presence of insulators whether they actually occur in the insulators proper or elsewhere will be charged to insulator leakage.

It is convenient to divide insulator leakage into several sources. This division is an arbitrary one, because some of the sources are not independent of each other and are, as will be seen later, difficult to separate experimentally.

The division follows:

A-c. and d-c.	A.	Leakage directly through insulator material to pin.
	B.	Leakage directly over insulator surfaces from line conductor to pin.
A-c. only.	C.	Dielectric absorption in insulator material.
	D.	Dielectric absorption in pins.
	E.	Displacement current losses in crossarms and pins.
	F.	Losses due to unbalanced displacement currents in external resistances such as those of crossarms, poles, etc.
	G.	Displacement currents flowing over insulator surfaces through high resistance.

It should be noted that while all the items play a part in a-c. leakage only the first two enter in the d-c. case.

These items[2] will now be discussed individually and will be treated generally as they exist under wet rather than dry weather conditions. In this connection most of the experimental evidence that will appear was obtained from tests on insulator test lines located near Phoenixville, Pa. The measuring equipment employed there has already been described in another paper[3] and for lack of space will not be further discussed here although certain improvements have been made since that paper was prepared.

Item A—Direct Leakage To Pin

This item refers to that leakage through the insulator material which is directly due to the conductivity of the material, for example via path *a b*, Fig. 1. Item *A* has been listed chiefly for completeness because it is fairly well known that for most materials commonly employed, this source of leakage is very small. In the present study it has been found to be negligible in magnitude.

Item *B*, therefore, becomes the controlling source of leakage for direct current and accordingly deserves consideration. However, it will be given even more consideration because its magnitude, being so closely dependent on the shape, size, location, and condition of the insulator surfaces throws light on those factors which will later be shown to play a very large part in leakage for alternating currents.

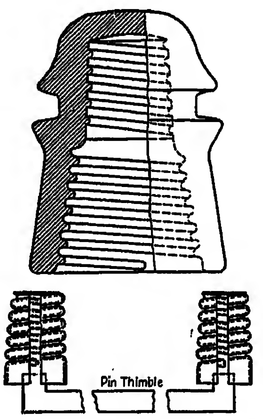

Fig. 3—Standard C. W. Insulator and Pin Thimble

Item B—Direct Surface Leakage

1. *General Characteristics.* Item B refers to that leakage over the insulator surfaces which is directly due to the conductivity of those surfaces, for example, via path *a c d e*, Fig. 1.

The outstanding characteristic of this type of leakage is the enormous changes in magnitude it exhibits under changing weather conditions.

For example, Fig. 4 shows the results of measurements made on a telephone line in Texas equipped with insulators of the type shown in Fig. 3. This test, made in clear weather, shows the large change in leakage produced simply by the condensation of moisture on the insulator surfaces. The peak value may be seen to be about 2500 times the smallest value measured.[4] Had

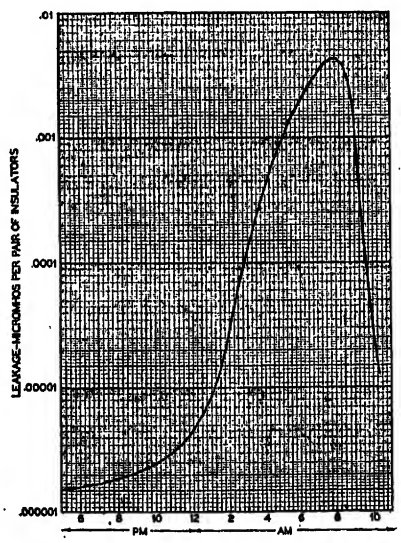

Fig. 4—Illustrates Large Variation of D-C. Surface Leakage in Dry Weather

2. The existence of several of these factors appears to have been well appreciated by Mr. R. D. Mershon as early as 1908, although Mr. Mershon's measurements were made at frequencies below 100 cycles where many of the items are extremely small in magnitude. See *High Voltage Measurements at Niagara*, by R. D. Mershon and Discussion, A. I. E. E. Trans., Vol. 27, 1908, pp. 845-929.

3. See *Methods of Measuring the Insulation of Telephone Lines at High Frequencies*, E. I. Green, A. I. E. E. Trans., Vol. 46, 1927, p. 514-519.

4. Such tests indicate the negligible effect of Item A.

it rained along the entire length of line the peak might readily have been 10 times greater and the corresponding ratio would have been 25,000. These ratios are higher than would be commonly found because the line was quite new but they serve to indicate the wide range in the magnitude of this type of leakage.

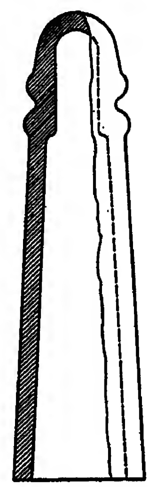

FIG. 5—EXPERIMENTAL DESIGN WITH LONG SKIRT

Fortunately, direct surface leakage even at its higher values in a sufficiently small part of the total leakage, especially at carrier frequencies, to make its wide variations substantially less serious than the foregoing ratios have indicated.

2. Influence of Insulator Design. To make this leakage conductance small it will be apparent from elementary considerations alone that the length of the path should be as great and its cross-section as small as possible. The latter depends on both the thickness and width of the moisture film, the width, in turn, depending upon the diameter of the surfaces.

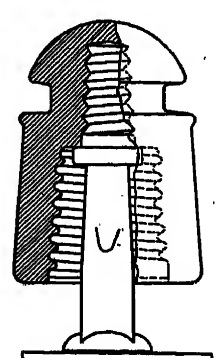

FIG. 6—EXPERIMENTAL DESIGN WITH SHORT CORRUGATED SKIRT (C. P.) MOUNTED ON STANDARD STEEL PIN

The length of path may be increased by simply lengthening the insulator. The cross-section of the film may be made small by decreasing the diameter of the surfaces. Both methods are employed in the experimental design shown in Fig. 5 which will be recognized as extreme, at least with respect to mechanical strength. This design under test gives excellent performance for direct surface leakage, having under various weather conditions from one to 25 per cent as much leakage as the more reasonable design shown in Fig. 6.

Another, but somewhat less effective way of increasing the length of path is the use of one or more petticoats. This method has a mechanical advantage in keeping the over-all insulator length small but the effectiveness of the longer path is partly lost due to the necessary increase in diameter. An example of this method is the design shown in Fig. 1 which gives about half as much leakage as that of Fig. 2.

Still another way of increasing the length of path is the use of corrugations (Fig. 6, for example). The data at hand while not conclusive, indicate that corrugations are of questionable value.

The third dimension of the conducting path, namely its thickness, can be controlled to some extent by insulator design. The thickness of the water film is determined by the rate of rainfall and by a balance between the forces tending to make the film adhere to the surfaces and the force of gravity tending to pull the water away.

To reduce the amount of water intercepted by the insulator for a given rate of rainfall, it is again advantageous to make the insulator diameter as small as possible.

To facilitate the running off of the water intercepted, the surfaces in the conducting path should be nearly vertical and smooth. These remarks apply mainly to the outside surfaces.

As to the inside surfaces the situation is somewhat different. These are protected from direct rainfall and become wet by splashing, condensation, creepage, and by moisture carried by air currents.

To prevent splashing from the crossarm it might appear desirable to provide the insulator with a wide flaring kind of shed but experience has shown that such sheds may be quite ineffective or even detrimental. It will be convenient to discuss the action of one type of shed later.

It has been found preferable to employ an insulator of small diameter. The effects of the splashing can be reduced by placing the insulator higher from the crossarm and by restricting the area of the opening between the pin and the insulator where the rising drops of water must enter.

These drops may readily rise a foot or more as casual observations show. To raise an insulator completely out of range obviously would lead to a cumbersome and mechanically unsatisfactory construction. However, some advantage may be had in elevating the insulator.

For example, consider Fig. 7 which shows the insulator of Fig. 6 mounted on a long pin. This pin, which was designed for another purpose, has an enlarged section which restricts the area between the pin and the insulator. The improved performance is, therefore,

the result of two effects: one, that of elevating the insulator; the other, that of restricting the area between the pin and the insulator.

An attempt was made to separate these effects by providing a third set-up in which the insulator is mounted on the pin of Fig. 6, this short pin being supplied with a rubber washer of the proper size and location to simulate the enlarged section of the long pin.

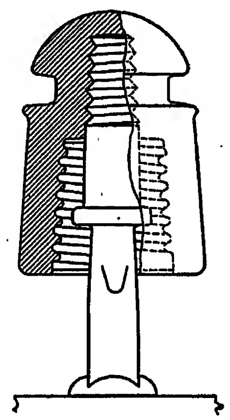

FIG. 7—C. P. DESIGN ON LONG STEEL PIN WITH BAFFLE

The relative performance of these three arrangements is given in Fig. 8 where S stands for short pin; $S\,B$, short pin with baffle; and $L\,B$ long pin with baffle. These results were obtained during a hard shower within a month after the installation of the rubber washers and give some idea of the effectiveness of the two expedients.

In discussing the influence of insulator design on this type of leakage the question naturally arises as to the part played by the pin on which the insulator is mounted.

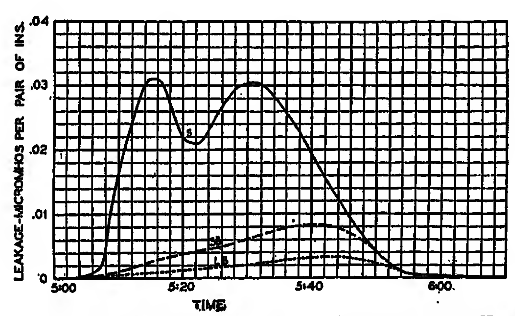

FIG. 8—ILLUSTRATES EFFECT OF PIN LENGTH AND BAFFLE ON D-C. SURFACE LEAKAGE

Wood pins of the type commonly employed on telephone lines are found to contribute somewhat to the total insulation, depending on the dryness of the wood and on the efficiency of the insulator itself.

The effect of the pin may be measured by comparing insulators mounted on wood pins in the standard manner with similar ones mounted on wood pins which have been covered with a thin metal foil, the coatings of a pair of pins being electrically joined. Thus, both the pins and the crossarm between them are short circuited.

Fig. 9 shows the results of such a test on the type of insulator shown in Fig. 1. At the start of the rain and during the first few hours the wood appears to reduce the leakage considerably but as the rain continues and the pin takes up moisture its effect seems to decrease to nil.

While similar tests on this and other types of insula-

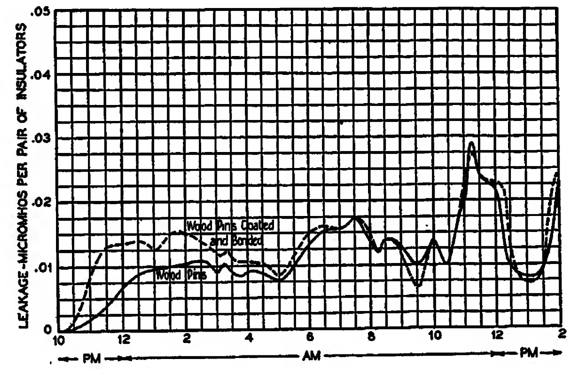

FIG. 9—ILLUSTRATES EFFECT OF COATING AND BONDING OF WOOD PINS ON D-C. SURFACE LEAKAGE

tors give corresponding results, still other tests indicate that at times, the wood continues to help out for many hours. One such test covering a period of about 23 hours showed, for this same type of insulator (Fig. 1), that the wood pin reduced the leakage by 30 per cent on the average.

On the other hand, similar tests for the design of insulator shown in Fig. 10, very frequently show the pin to have negligible effect.

While the foregoing tests have shown an advantage in favor of the wood pin, that conclusion holds only for the conditions of the test; namely, both wood and metal

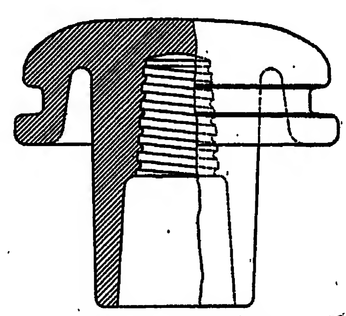

FIG. 10—EXPERIMENTAL DESIGN (C. D.)

pins having the same diameter. When an insulator is specifically designed for a metal pin both the pin and insulator diameters can usually be made small because of the greater mechanical strength of the metal pin. The advantages of the design of small diameter, as previously discussed, may readily offset the slight disadvantage of the metal pin and the net result may be an actual gain.

3. Influence of Insulator Material. While the insulators are new, the molecular attraction between the

insulator material and water plays a very important part; so important, in fact, that tests on such new insulators frequently give an unreliable basis on which to make decisions. On new glass insulators and particularly on those of borosilicate compositions, the rain water does not seem to wet the surfaces but rather stands in individual separate drops. The phenomenon is so marked that the surfaces have the appearance of having been oiled or waxed.

Under such conditions the conducting path is broken up and is discontinuous. Naturally its conductivity is very small. It would be fine if this property of the material could be preserved. Unfortunately along with exposure to weathering there comes an increasing tendency for the drops of water to spread out and unite to form a continuous path. Apparently, this action results from the collection of impurities on the surfaces, for such molecular phenomena are well known to be very sensitive to any contamination.

The direct surface leakage has been observed generally to increase 10 or more times after only a few weeks exposure. In one particular case where it rained the same day that the new insulators were installed, their surface leakage was observed to be less than one per cent of that measured on insulators of the same shape and material which had been aged for about two years.

This study of insulators has shown that while changes in design may affect changes in direct surface leakage by a factor of, say, 10, changes in kind of material affect this leakage by a factor of two or less after long exposure. In general, then, the material may be said to be less important than the design. Purely general considerations indicate this conclusion in view of the surface nature of the phenomenon. Consider an insulator of a given design exposed to the elements for several years. More and more foreign matter will collect on the surfaces as time goes on. It is obvious that as this process continues, the insulator material is becoming less and less important and it is conceivable, at least, that given time enough, this surface of foreign matter would determine the insulator performance irrespective of the material beneath this surface coating. At this point, design is paramount.

However, the material might be expected to influence the aging process in some way. From this viewpoint smoothness and hardness of surface, together with chemical stability, appear to be desirable qualities.

This study has been confined chiefly to various kinds of glass. In general, these have all had smooth surfaces, but they have varied in hardness and chemical stability. For example, borosilicate glasses are said to be generally harder and chemically more stable than the common alkali group.

The relative performance of one sample from each of these respective groups is given in Fig. 11. Both were molded to the design of Fig. 12. This particular test which was made after more than a year of exposure shows only a small difference between the two glasses. A previous test (exposure of nine months) showed quite the same results while still earlier tests had indicated the borosilicate as quite superior to the alkali glass.

While the foregoing tests illustrate the point made above as to the relative importance of design *vs.* material they cannot be considered as conclusive evidence on the relative merits of these two glasses for direct surface leakage.

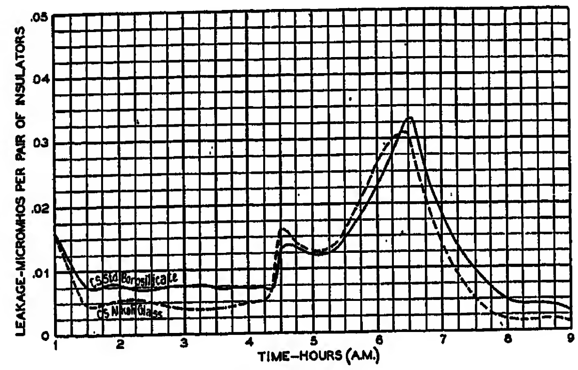

Fig. 11—Illustrates Effect of Insulator Material on D-C. Surface Leakage

Probably more important than either hardness or chemical stability, which directly affect surface leakage, is the transparency of the material which affects leakage only indirectly, through the medium of insects apparently small spiders. These spiders build nests on the inner surfaces and seem to prefer dark or dimly lighted spaces for their homes. Therefore, the more transparent the insulator, the less attractive home it makes; and of opaque materials, probably white ones are accordingly less attractive than dark colored ones.

Other factors which enter into the spiders' choice appear to be those of space and of protection from the elements. These latter factors are functions of insulator design rather than material.

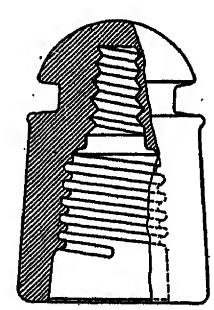

Fig. 12—Standard C. S. Design for Use With Standard Steel Pin

There has been little opportunity to study these factors on the insulator test lines, due to the lack of spiders. Only one specific case has been found where their effect was marked. This was a case where small borosilicate insulators were given an opaque metal coating. After this coating had been on several months the direct surface leakage increased to several times the value for the similar uncoated ones. An investigation

showed spider nests under many of the coated insulators.

On the other hand, several types of larger insulators have showed no such effect when coated, although some of these have been exposed for several years. These results are not conclusive. They merely indicate that design, as well as transparency of material, is a factor.

An experience of the telephone plant in the use of opaque insulator material (porcelain) showed a serious reduction of efficiency after a few years of exposure, apparently explained by the action of inserts.

4. Specific Conductivity of Film. The specific conductivity of the rain itself before it reaches the insulators is determined by the nature and amount of impurities collected in its fall. Both the kind and amount of impurities must vary greatly in different localities, for example, industrial centers as compared with open country. Then again, the amount in any given locality must vary throughout any storm on account of the cleansing action of the rain on the atmosphere.

On reaching the insulators the rain will suffer a further increase in conductivity depending on the impurities it finds there. Smooth vertical surfaces should be advantageous in reducing the collection of dust.

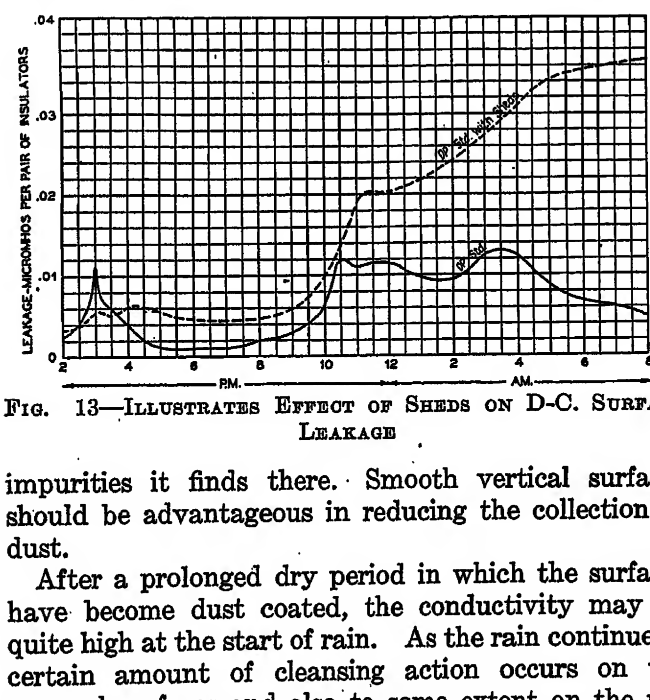

FIG. 13—ILLUSTRATES EFFECT OF SHEDS ON D-C. SURFACE LEAKAGE

After a prolonged dry period in which the surfaces have become dust coated, the conductivity may be quite high at the start of rain. As the rain continues a certain amount of cleansing action occurs on the exposed surfaces and also to some extent on the unexposed surfaces, depending on the splashing. A decrease in leakage corresponding to this cleansing action has occasionally been observed.

Thus, in a locality where rain is infrequent but where dew, for example, might wet the insulators, the leakage might conceivably be quite high.

This phenomenon can be produced artificially and emphasized by placing roofs over the insulators, thus preventing any direct cleansing action of the rain.

Roofs of sheet metal six inches in height, five inches in width and twelve inches in length were placed over insulators of the design in Fig. 1. The ends were left open to permit passage of line wire.

While still new and clean these protected insulators showed less leakage than the unprotected ones of the same design. However, after a few months the protected insulators became covered with a thick layer of dust blown under the roofs by wind. Then when it rained, enough moisture reached the surfaces to wet the dust, but not enough to have much cleansing action. The surface leakage then becomes very high, as will be apparent from Fig. 13.

ITEM C—DIELECTRIC ABSORPTION IN INSULATOR MATERIAL

1. General Characteristics. When a dielectric is subjected to a varying potential field a certain amount of the electrical energy is dissipated in the material in the form of heat, depending on the nature of both the material and the field. This phenomenon is commonly called dielectric absorption.

Such a field exists between the line and tie wires on one side and the pin on the other. The insulator material lies more or less in this field and, therefore, dielectric absorption is naturally to be expected. While it is convenient to refer to a single insulator it should be remembered that two insulators are in series between wires at any one point.

The chief characteristic of the leakage resulting from this phenomenon is its variation with frequency. Approximately, it increases directly with the frequency. In the voice range its magnitude is generally negligible, but may become appreciable in the carrier range, particularly at the upper end.

Item *C*, like item *B*, increases in wet weather, but to a far less degree. This increase, which is brought about by the enlargement of the field caused by the wetting of the insulator surfaces, cannot be directly separated from the increases in the several other sources. Indirectly, however, a general idea of the magnitude of item *C* in wet weather can be obtained in the following two ways.

Both methods are based on the observation that the increase in capacitance between the wire and pin produced by metal-coating the outside of the insulator is invariably greater than the corresponding increase caused by wetting the uncoated insulator. For example, the increase due to coating the insulator of Fig. 3 exceeded the maximum increase observed for any rain by at least 40 per cent. More commonly this figure would be 100 per cent both for this and other shapes.

Therefore, if such metal-coated insulators (mounted on bonded metal pins for reasons appearing in the discussion of items *D* and *E*) be measured in dry weather the leakage conductance so found is likely to exceed by a substantial amount the wet-weather value of item *C*.

Another procedure consists in calculating the leakage of the metal-coated insulator. This method requires a knowledge of the wire-to-pin capacitance and the phase angle of the insulator material.

Fig. 14 shows the measured value for the insulator of Fig. 1 when molded from a clear flint glass. The phase angle of this particular glass is not known. However, the wire-to-pin capacitance is known. Using this known value, the leakage has been calculated for two measured values of phase angle for flint glasses, between which the value of this particular glass probably lies.

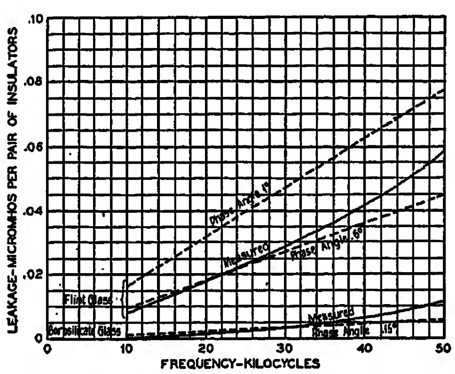

Fig. 14—Variation of (C) With Frequency for Standard D. P. Design

Similarly, the measured and calculated leakage are shown for this same design of insulator when molded from a borosilicate glass of known phase angle.

Neither method is capable of high accuracy, but they need not be for our present purpose of determining the order of magnitude of item C.

Consider item C at 50 kc. where its relative importance is greatest. At this frequency the metal-coated flint-glass insulator gave a measured leakage which is only about 10 per cent of the total wet-weather leakage of such an insulator as commonly used uncoated. So it appears that even at this high frequency, item C is less than 10 per cent of the total leakage of this particular design and material. This particular sample of flint-glass is not the best of the common alkali glasses nor is it the worst; so this round number of 10 per cent is a fair average value to use for alkali glasses.

The corresponding value for the borosilicate glass of which the sample was representative is about 4 per cent.

2. Influence of Design. The absolute magnitude of item C is influenced somewhat by design because of the effect of shape on capacitance. An idea of the magnitude of this effect can be obtained by comparing Fig. 14 with Fig. 15. Both designs were cast from the same batch of glass so that material plays a small part in comparing the two designs.

In general, for a given size of pin, the capacitance is decreased by enlarging the insulator diameter, particularly at the wire groove. Similarly, for a given outside diameter, the capacitance is decreased by making the pin diameter less. In general, too, the shorter the insulator, the less the capacitance.

Through the ordinary range of shapes the absolute magnitude of item C will not vary more than about three to one, and expressed as a percentage of the total wet-weather leakage, it is doubtful if item C, in the worst combination of poor design and poor material studied, could reach as high as 20 per cent.

The foregoing remarks apply to insulators on metal pins. When wood pins are used, the capacitance is less and C is correspondingly less. If the pin is dry, C is extremely small, if the pin is wet, C is still considerably less than it is for the same insulator on a metal pin.

3. Influence of Material. The range of the absolute value of C for various kinds of glass is much greater than it is for various designs. Phase angle of the material is frequently used as a criterion but Hoch[5] has shown that for insulator purposes, the product of phase angle and dielectric constant is a better criterion. Using the latter, a range of more than 20 to 1 is found for the glasses studied.

From the standpoint of item C alone, on account of its small relative magnitude there is little justification in going to high grade glasses, especially as these are more costly, unless other sources are first reduced sufficiently to make C really important.

Item D—Dielectric Absorption in Pins

1. General Characteristics. Item D applies only to pins of dielectric material (usually wood) or to metal pins with cobs of dielectric material.

Like C, D is roughly proportional to the frequency and its importance is greatest at the upper end of the carrier range of frequencies.

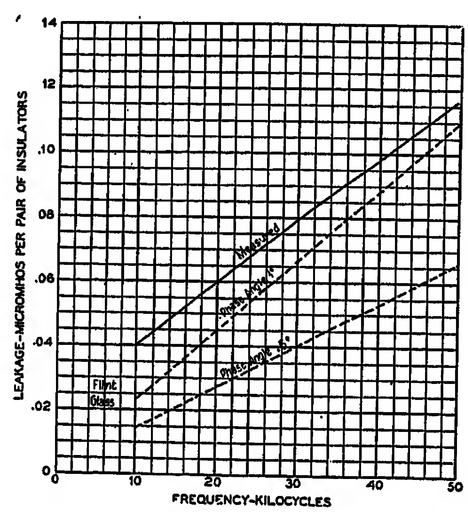

Fig. 15—Variation of (C) with Frequency for Standard Toll Design

Again, like C, D increases in wet weather due to the accompanying increase in wire-to-pin capacitance. It also increases because of absorption of moisture by the pin.

Fortunately, due to the small value of C, particularly when dielectric pins are used, a rough measure of D can

5. See "Power Losses in Insulating Materials," E. T. Hoch, *Bell System Technical Journal*, Vol. 1, No. 2, November 1922, pp. 110-116.

be obtained by again making use of metal-coated insulators.

Fig. 16 shows two measurements of the leakage in dry weather of metal-coated insulators on wood pins. These insulators are similar in shape to that of Fig. 1, and were molded of a borosilicate glass.

Due to the low capacitance when wood pins are used and to the high quality of glass, item C can be neglected here.

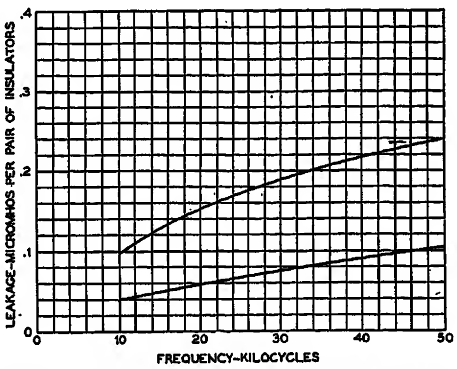

Fig. 16—Variation of (D) with Frequency for Standard D. P. Design

Item E, which is to be discussed in the next section, enters here to some extent, but the cross-section of the crossarm is so much greater than that of the pins that this item, while it cannot be neglected, is probably small.

The measured leakage then closely represents that due to dielectric absorption in the pins under the conditions of the test, namely, metal-coated borosilicate insulators.

To the extent that metal coating gives greater capacitance than does wetting the insulator the value of D is magnified by these measurements. On the other hand, to the extent that the capacitance is reduced by the high quality of glass, the measurements give too low a value of D for alkali glasses.

As these effects approximately balance each other, the measured values are fairly representative of D for the alkali group.

The difference in the two values measured at different times is mainly due to the moisture content of the pins, the higher value corresponding to the higher moisture content.

Consider the insulator of Fig. 1 made of alkali glass and mounted on wood pins. Item C will be small, very small when the pin is dry; and while appreciably larger when the pin is wet, it is still considerably smaller than its value for a metal pin of the same dimensions. D, on the other hand, is large, even when the pin is dry; so in this example, D may be said to be considerably more important a factor than C.

In the case of this same design molded from a borosilicate glass, D becomes relatively even more important a factor.

2. Influence of Design. The general remarks which applied to C as to insulator diameter and length and as to pin diameter apply to D.

3. Influence of Insulator Material. For a given design, the lower the dielectric constant of the insulator material, the lower D will be.

4. Influence of Pin Material. Some study of this subject has been made, but the results are not sufficiently conclusive to report.

Item E—Displacement Current Losses in Crossarms

1. General Characteristics. This item will first be considered as it applies to insulators on metal pins. The path of the displacement current is as follows: the current passes from one line wire through the capacitance of the one insulator to its pin, thence through the crossarm to the other pin and finally through the capacitance of the other insulator to the other wire. The capacitances of the two insulators are thus in series. The adjective "displacement" has been applied to the current because its magnitude is mainly determined by the insulator capacitance.

The losses produced in the crossarm by this current obviously depend on the electrical equivalent of the crossarm and on the insulator capacitance. If the former were a pure resistance with a magnitude small compared with the reactance of the series capacitances, then E would increase approximately as the square of the frequency. Experimentally, E is generally found to increase at a rate lying between the first and second power of the frequency over the range studied.

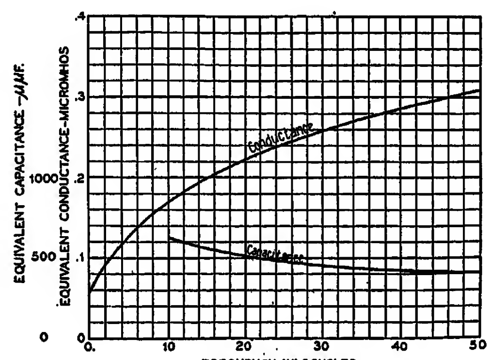

Fig. 17—Variation of Equivalent Parallel Capacitance and Conductance with Frequency for 25 Crossarms in Parallel Dry Weather Measurement

A knowledge of the electrical equivalent of the crossarm, together with the insulator capacitance, permits E to be calculated.

The constants of the crossarm between steel pins six inches apart, as measured on a dry day, are given in Fig. 17. From this measurement, the magnitude of E has been calculated for individual insulator capacitances of 4 and 20 m. m. f., and the results are shown in Fig. 18. The capacitances of most of the insulators studied lie within these two limits.

Fig. 18 also shows the value of E as measured for the insulators of Fig. 19. This measured value of E was obtained as follows: The leakage of the insulators was measured first with the crossarms short-circuited by tying a wire from each pin to the other. Then the wires were removed and the measurement repeated.

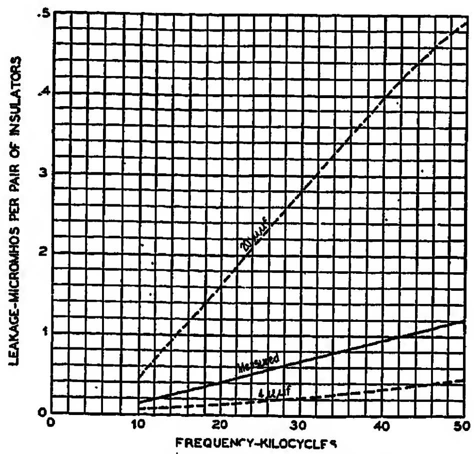

FIG. 18—VARIATION OF (E) WITH FREQUENCY IN DRY WEATHER

The difference between these measurements is E, if other sources are assumed to have remained unchanged. This assumption appears justified from the following test of its validity. The measurement of E, together with the measured constants of the crossarm, enables the insulator capacitance to be calculated. Such a calculation has been carried out and the value of capacitance so obtained checks very closely the value obtained by direct measurement.

The curves of Fig. 18 show that E may be large in dry weather. In fact, it is generally several times the magnitude of item C in dry weather and at the upper frequency range. Therefore, E is the controlling factor in dry weather.

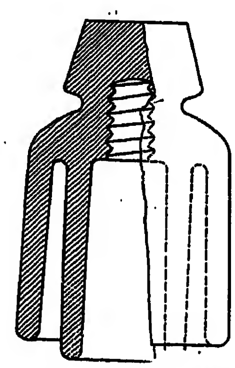

FIG. 19—BRITISH POST OFFICE DESIGN

As to the effect of weather conditions on E, the increase in insulator capacitance brought by wet weather tends to greatly increase the losses. On the other hand, the large decrease in the crossarm impedance resulting from rain tends to decrease the losses. As a net result of these opposing effects, E is generally less in wet than in dry weather. In fact, after several hours of rain, E has been found to be almost negligible.

The upper curve in Fig. 20 shows E for the insulator of Fig. 1 foil-coated and mounted on steel pins with composition cobs. This curve was obtained in dry weather. The lower curve of Fig. 20 shows the magnitude of E for the same insulators after 1½ hours of rain.

The equivalent conductance of the crossarms varies over a wide range depending on the weather. For instance, values of d-c. conductance 40 times as great as that recorded on Fig. 17 have been observed and the data indicated that still higher values are probable. The smallest observed value was one-tenth of that recorded in Fig. 17.

The experimental determination of the magnitude of E for insulators on wood pins is a difficult problem, because E cannot be readily separated from D.

The importance of insulator capacitance on E has already been established, so a knowledge of this factor for insulators on wood pins enables an estimate of E to be made.

For example, the insulator of Fig. 1 on wood pins gives a measured capacitance in dry weather of about

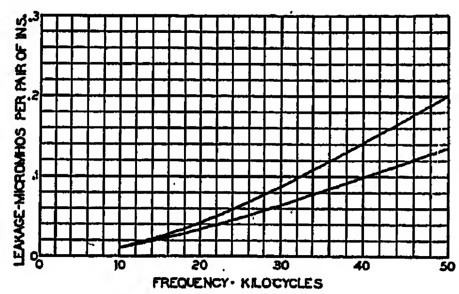

FIG. 20—MEASURED LEAKAGE DUE TO (E)

4 m. m. f. E for this value is given by the bottom curve of Fig. 18. In this particular example, E is quite small in dry weather. The general decrease in E accompanying wet weather indicates that this item does not contribute much of the leakage of insulators on wood pins, at least after the crossarm is very wet.

2. Influence of Insulator Design. The wire-to-pin capacitance varies perhaps three to one for the designs covered in this study. The corresponding range in E is obviously great. Therefore, insulator design has an important influence on the magnitude of E.

3. Influence of Insulator Material. The materials studied have not shown a range in dielectric constant of more than about two to one. The corresponding range of wire-to-pin capacitance is even less; so insulator material may be said to have a relatively small influence on E.

4. Influence of Pin Spacing. Item E is naturally expected to be influenced by the pin spacing. However, the data bearing on this effect are too meager to report.

Item F—Losses Due to Unbalanced Displacement Currents Flowing in External Impedances such as Crossarms, Poles, Etc.

1. General Characteristics. In general characteristics, F is very similar to E. As E is caused by a displacement current which flows directly from one line wire to the other via the crossarm in the manner already discussed, so F is similarly caused by unbalanced displacement currents flowing through crossarms, poles, etc. There is not sufficient space in this paper either to present details of the theory of these losses or to describe the many interesting tests made to illustrate the effect.

In brief, F is due, first, to any difference that may exist between the capacitance of the insulator on one wire and that on the other wire, and second, to other unbalances in capacitance such, for example, as those caused by the presence of other wires.

The first of these causes will be recognized to be very similar in nature to a second order effect of E and is accordingly small in magnitude, at least if the same kind of insulator is employed on each wire; so F, due to this particular cause, is normally small.

The second source is the more important one. F, resulting from it, is greatest in dry weather, like E. Here, F's importance is so great that transpositions in the insulator test line were found necessary, despite the line being only 200 ft. in length. The dry-weather leakage of many of the insulators under test is so small that, without transpositions, errors caused by the presence of other wires have amounted to several hundred per cent.

The variation of F with frequency is much the same as E.

Also, like E, F is less in wet than in dry weather.

The general remarks made in the discussion of Item E regarding the influence of insulator design and material apply also to F.

For the well transposed lines used for carrier circuits and for the reasonably well balanced insulator capacitances that the standard construction gives, F contributes little to the total wet-weather leakage.

Item G—Displacement Currents Flowing Over Insulator Surfaces through High Resistance

1. General Characteristics. Over the carrier range of frequencies this item is the most important source of leakage in wet weather. It probably contributes more than all other sources combined. On this account, it may not be amiss to repeat here an already known theory which fits the results of the present study fairly well.

Consider an insulator, the outside of which is wet. Divide this surface into elements of area and take, for example, one of them near the bottom of the insulator. Assume a small displacement current to flow from the pin to this element through the small capacitance which exists between them. Now for this current to reach the wire, it must flow through the thin film of moisture lying between the element chosen and the wire. This film offers a high resistance to the current, not high enough, however, to seriously limit the current, but, nevertheless, sufficient to produce heat losses. These losses when integrated over the entire insulator surface become important and qualitatively, at least, account for the characteristics of item G.

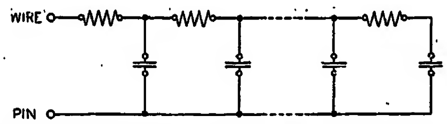

Fig. 21—Electrical Equivalent of an Insulator for the Production of (G)

Fig. 21 shows in much simplified form an electrical equivalent of this action. An inspection of this figure will throw some light on the subject.

For one thing, it is clear that the apparent wire-to-pin capacitance will decrease with increasing frequency. Wet-weather tests invariably show this effect. (Incidentally, this effect tends to reduce the magnitude of C and D, at the higher frequencies.)

It is also apparent that the conductance of this simplified circuit is zero at zero frequency and a maximum at very high frequencies. In the intervening range the conductance at first rises nearly as the square of the frequency, then the relations becomes more nearly linear and finally tapers off to a final constant maximum value.

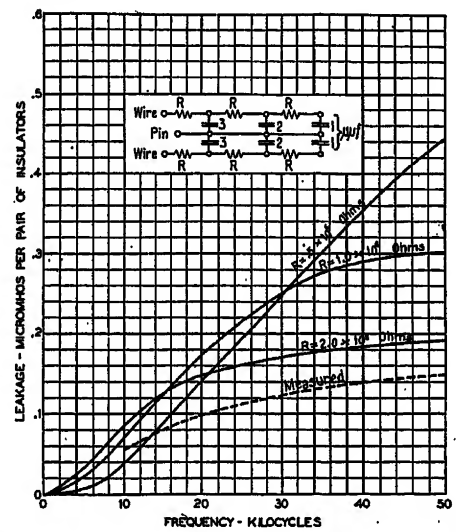

Fig. 22—Calculated and Measured Value of (G) for C. P. Insulator

If the distributed capacitance of an insulator were accurately known, as well as the resistivity of the surface film, the magnitude of G could be calculated. Unfortunately, both factors are difficult to determine with precision.

However, it is useful to carry out such a calculation, even though the factors be not accurately known.

Fig. 22 shows the variation of G with frequency,

as calculated for the assumptions indicated on the drawing. The assumed distributed capacitance and surface resistivity are intended to represent those of the insulator of Fig. 6. A measured value of G for this insulator is shown by the dotted curve. The agreement is not very good, being no more than qualitative. However, the accuracy of the assumptions is not sufficiently high to expect a much better agreement.

In accordance with this theory, it is evident that G could be produced on a dry insulator by coating the surface with a thin metallic film of high resistance. This has been checked experimentally. The dry-weather conductance of an insulator of given shape and material can readily be increased ten or more times by such a coating. In its general magnitude this increase corresponds to that of the uncoated insulator between dry and wet weather.

Referring again to Fig. 21, G will be seen to be zero when the resistivity of the circuit is zero. Thus, if a metal coating of low resistance be placed on the outside surface, the value of G would be made negligible for that surface. However, such a coating causes the losses on the inner surfaces to increase. The net result is usually a substantial reduction in leakage, as shown by many tests comparing coated with uncoated insulators.

2. Influence of Insulator Design. From the foregoing discussion, the importance of insulator capacitance is quite apparent. For G to be small, it is not only desirable that the total capacitance shall be small, but particularly that any capacitance remote from the wire groove be small, unless the resistance of the path from wire to that capacitance can be maintained at a very high value.

Insulator design is important from this standpoint. It is also important because of its relation to the resistivity of the surface film, as was discussed in some detail under B.

3. Influence of Insulator Material. In general, the influence of insulator material has been less than that of design, especially after the insulator has aged for a couple of years. The influence of material on G is determined both by the dielectric constant of the material and its surface resistivity.

While the dielectric constant of the materials tested varies about two to one, the corresponding range of G is very much less, on account of the low dielectric constant of the air which occupies a part of the dielectric path.

The factor of surface resistivity is probably the more important one. For example, its effect on G probably accounts for most of the increase in leakage at high frequencies that accompanies aging, which is a very substantial one.

As to the relative importance of these two factors, tests have been made on only one design. At this writing the tests register a slight balance in the favor of a good surface over a good (low) dielectric constant.

The influence of material on G, while not great, gives the chief justification from the electrical standpoint for employing the better but more costly glasses.

Conclusion

Description of New Insulators. Two new insulators are available for use on carrier circuits of the Bell System. These replace the standard D. P. insulator of Fig. 1 in those cases where the additional expense of the new insulators is justified.

One of the new types is designed for use on the wood pins of existing lines. It is known as the C. W. insulator and its design is shown in Fig. 3. The pair of pin thimbles illustrated at the bottom of that figure is first placed over the two wood pins, then the insulators are screwed into place over the thimbles, forcing the latter well into the threads of the wood. The thimbles are constructed of thin copper and are bonded together by a tinned copper strip.

The other new type is designed to screw directly over a steel pin. This is known as the C. S. insulator and its

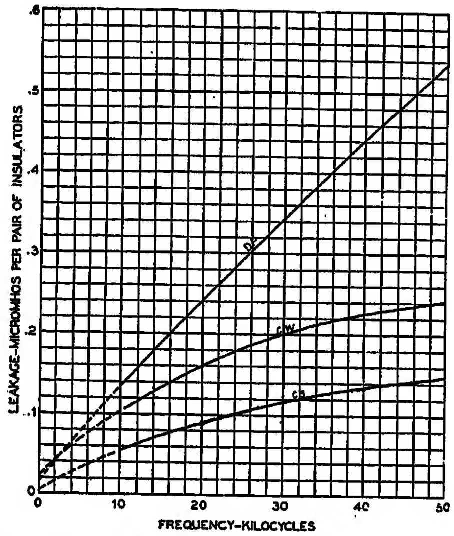

Fig. 23—Relative Leakage of D. P., C. W. and C. S. Insulators as Measured at Phoenixville, Pa., in Moderate Rain

design is shown in Fig. 12. At each crossarm the two steel pins are bonded by means of a wire underneath the arm.

Both new designs are molded from borosilicate glass. This glass is more expensive than the alkali glass used in the old D. P. design. On this account, and on account of the pin thimbles in one case and the steel pins in the other, the new insulators cost more to install than did the old ones.

Both of the new designs were brought out several years ago before this study had conclusively demonstrated the importance of surface losses (item G). It will, therefore, be of some interest to discuss their performance in the light of the more complete knowledge.

Performance of D. P., C. W., and C. S. Insulators. The leakage of these three types, as measured on the insulator test line at Phoenixville, Pa., in a moderate rain, is given in Fig. 23. This measurement does not

give a true picture of the relative efficiency of the three types because no two of them are aged alike. Besides, the relative efficiency varies considerably with different weather conditions. However, the measurement will serve our present purpose, which is to analyze the total leakage of each design and thus give a perspective which could not well be brought out in the detailed discussion of the several sources of leakage. It should be pointed out and emphasized that the allocation of the total leakage to its component parts can be only very approximate.

Fig. 24 shows an estimate of the leakage contributed by the several sources for the D. P. design. The leakage directly through the insulator material is negligible and item A, therefore, does not appear. Similarly, the leakage due to unbalanced displacement currents flowing in crossarms, poles, etc., is considered negligible and, therefore, item F does not appear.

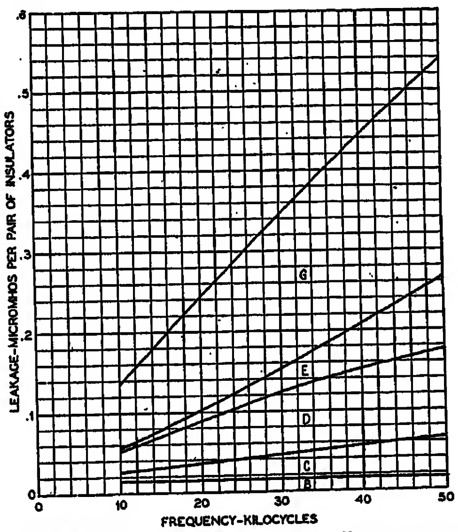

FIG. 24—ESTIMATED ALLOCATION OF LEAKAGE FOR D. P. INSULATOR

At a frequency of 30 kc., for example, B, the direct surface leakage or d-c. leakage, is about 5 per cent of the total. The dielectric absorption in the glass C is about 10 per cent. The dielectric absorption in the wood pins D is about 20 per cent. The crossarm losses E contribute about 10 per cent and, finally, the losses on the insulator surfaces G contribute about 55 per cent.

Fig. 25 shows a similar estimate for the C. W. design. Here the bonded pin thimbles shield the wood pins from any electric field and thus eliminate dielectric absorption D from the pins. Similarly, by short-circuiting the crossarms, the losses occurring there are eliminated. Accordingly, both items D and E are made negligible and do not appear.

Of the remaining factors, the direct surface leakage B contributes about 12 per cent of the total (at 30 kc., for example). The losses in the glass C are liberally estimated at about 5 per cent. Finally, the surface losses G contribute over 80 per cent of the total.

Comparing the C. W. performance in this test with that of the D. P. we find that most of the improvement shown by the C. W. has resulted from the elimination of items D and E. Due to the single skirt design of the C. W. and the pin thimbles, item B has been increased in magnitude. The loss in the glass C has been decreased by the use of borosilicate glass. However, the most important item G has been only slightly reduced, and if C. W. insulators in this test were aged as far as the

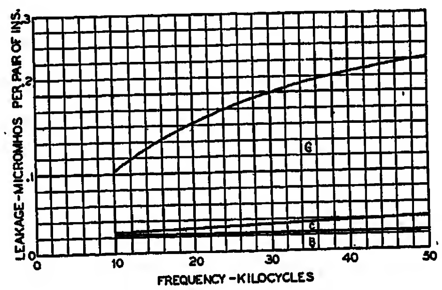

FIG. 25—ESTIMATED ALLOCATION OF LEAKAGE FOR C. W. INSULATOR

D. P., the C. W. might show no improvement with respect to G. The pin thimble construction tends to increase the insulator capacitance and thus tends to make G larger for the C. W. than for the D. P. design. The use of a borosilicate glass with its lower dielectric constant counteracts this action somewhat.

The estimated division of losses for the C. S. design is given in Fig. 26. The use of metal has eliminated any dielectric absorption D from occurring in the pins. The bonding of the pins by wire has eliminated crossarm losses E.

Of the remaining factors, the direct surface leakage B contributes about 4 per cent or less of the total at 30 kc. The losses in the glass C are liberally estimated at 10 per cent or less, while the surface losses G contribute about 85 per cent or more.

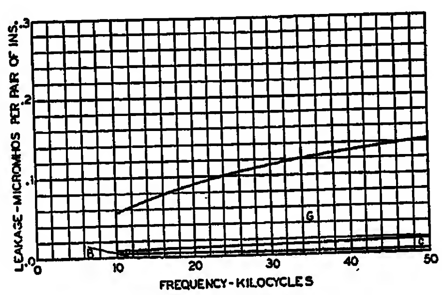

FIG. 26—ESTIMATED ALLOCATION OF LEAKAGE FOR C. S. INSULATOR

In this design the absolute magnitude of B has been decreased somewhat, chiefly because the small diameter of the steel pin permits a small diameter of insulator, the advantages of which were pointed out in the detailed discussion of this item.

The low capacitance made possible by the small steel pin has helped to make both C and G relatively small, although most of the improvement in C is due to the borosilicate glass.

The improvement in the surface losses G over the D. P. design is quite marked.

For the new designs the two factors B and G are the controlling ones. In this particular test B happens to be quite small in magnitude, and would naturally lead one to conclude that B had been made unnecessarily small at the expense of G, especially since these two items in many respects place conflicting requirements on insulator design. However, B has been observed at times to reach a value as high as one-third of the total leakage at 50 kc. The necessity of engineering for such cases makes the design more reasonable, especially when it is recalled that the insulators must serve for direct current and low frequencies, as well as for the carrier range.

Of the new designs, the electrical superiority of the C. S. over the C. W. design is apparent. This fact, together with economic considerations, has led to the almost universal choice of the C. S. rather than the C. W. type for the field of application of the new insulators in the telephone plant.

The utility of the C. S. insulators in the telephone plant will be more clearly apparent from a consideration of the reduction in attenuation which their use brings about.

The losses in transmission over a pair of wires at carrier frequencies come chiefly from two sources: one, substantially fixed in magnitude, depending mainly on the resistance of the wires; the other, quite variable in magnitude, depending on the leakage conductance between the wires and, therefore, on the weather.[6]

6. For a more detailed discussion of attenuation see a parallel paper, *The Transmission Characteristics of Open-Wire Telephone Lines*, by E. I. Green.

In the case of 165-mil copper wires on 12-in. spacing these two components of loss are approximately equal in wet weather when the older type of insulators are used. The C. S. type cuts this variable component about in half at 30 kilocycles thus reducing the total wet-weather attenuation of these wires to about 75 per cent of its former value. For smaller sizes of wires the percentage reduction is correspondingly less.

The benefits of the lesser attenuation can be utilized in the plant in various ways, depending on local conditions; for example, in increasing repeater spacing, in employing smaller gages of wires, or in increasing the number of insulators per mile to provide for better transposition designs.

In addition, the new insulators, in having reduced the variable component of loss, improve the stability of carrier circuits to a marked degree.

ACKNOWLEDGMENT

Only the electrical features of the new designs have been discussed. Closely related to these are the many mechanical problems which naturally arise in new construction. These latter problems, during the development of the new designs, came under the supervision of Mr. C. S. Gordon, assisted by Mr. J. T. Lowe.

The Corning Glass Works has cooperated in molding special experimental insulators of various compositions.

Data on the electrical properties of numerous glass compositions have been supplied by the Bell Telephone Laboratories.

The writer desires to express his thanks to Messrs. F. A. Leibe, L. R. Montfort and L. Staehler for assistance in the measurements and to Mr. H. R. Nein for assistance in the preparation of this paper.

A General Switching Plan for Telephone Toll Service

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Fellow, A. I. E. E.

Synopsis.—This paper outlines a comprehensive plan for improved switching of long haul toll telephone traffic in the United States and eastern Canada. A brief discussion is given of the methods of designing the toll plant to give adequate transmission efficiency for all connections established in accordance with this plan, including a new method of providing amplification at intermediate switching points replacing the cord circuit repeater method.

* * * * *

Introductory

On January 25, 1915, telephone service was, with due ceremony, inaugurated between the Atlantic and Pacific Coasts of this country. This occasion marked a great step forward both technically and commercially. Before that time, the limit of practicable telephone transmission had been about 1500 miles. The transcontinental service was made possible by the completion of numerous important developments and particularly by the perfection of telephone repeaters and of means for applying them to long wire circuits.

Until then the Pacific States and their neighboring states had been isolated telephonically from the eastern and midwestern parts of the country. The demonstration of commercially practicable telephone circuits across the continent gave a great impetus to the idea of universal service, that is the provision of a telephone plant such that telephone service could be given at commercially attractive rates between any two telephones in the country.

In the fifteen years since the opening of the first transcontinental circuits, the ideal of universal service has to a large extent been realized. Practically all the telephones of the United States and a large part of Canada now have provision for connection with the countrywide toll telephone network, more than 99 per cent being included. To achieve universal service, however, involves a great deal more. Circuits must be provided in such numbers and so arranged that connections between any two telephones can be established quickly and without too many intermediate switching points. Also the telephone plant must be designed for such standards of transmission that these connections, when established, will permit satisfactory conversation. In general, the technical advances which have been made during the last fifteen years to achieve the present standards of toll service have been described from time to time before the American Institute of Electrical Engineers, and it is not within the scope of this paper to review them.

Associated with this development of the telephone plant has been a very rapid increase in traffic. Fig. 1 indicates this increase in the United States and Canada since 1915. A striking characteristic of this growth is that the increase has been much more rapid for the longest lengths of haul than for the shorter lengths of haul. For example, during the last five years in which

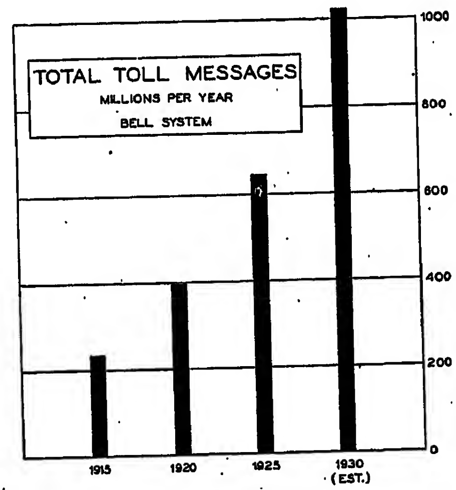

Fig. 1

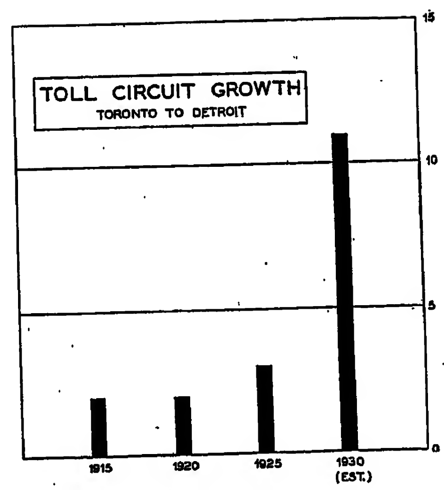

Fig. 2

the messages on lengths of haul up to 250 mi. approximately doubled, the messages on hauls from 250 to 1000 mi. increased five times and those over 1000 mi. increased more than ten times. This characteristic is also illustrated in Figs. 2, 3, and 4 which show respec-

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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tively the growth in the number of circuits between Toronto and Detroit, 240 mi. in length; Buffalo and Chicago, 550 mi. in length; and direct circuits from New York and Chicago to the Pacific Coast, averaging about 2500 mi. in length. This particularly rapid growth in very long haul traffic has made it practicable to establish a considerable number of long-haul circuit groups and has greatly assisted in the problem of hand-

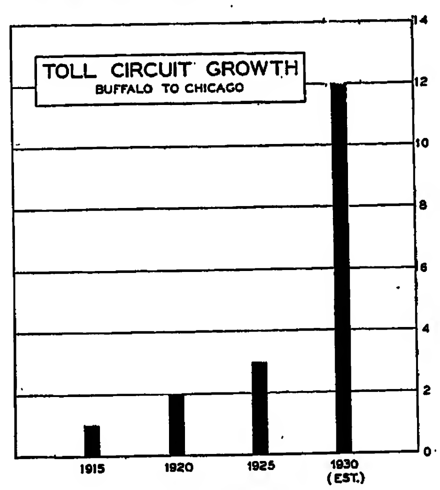


Fig. 3

ling satisfactorily calls between widely separated points. It has led to the condition today in which 74 per cent of the long distance (Long Lines) messages are handled over direct circuits and 20 per cent with one intermediate switch.

The part of the business on which it is most difficult to give a high grade of service is naturally the scattering business between widely separated points. In these cases each item of traffic, that is the business between two specific points, is relatively small but the number of items of traffic is great. The number of messages involved in each item of traffic does not justify direct circuits and in very large numbers of cases it is necessary, in order to provide a connection, to make more than one intermediate switch. This applies at present to six per cent of the long distance telephone business of the country. All measures of the quality of service—speed, accuracy, and transmission—show that the difficulty of handling the service satisfactorily increases rapidly with the number of intermediate switches involved.

The development of the toll business has led to a great increase in the amount of business between large numbers of widely separated points. There has also been an extensive trend toward concentration of the plant used in handling the business in important toll offices and along important routes. The long haul toll business is now handled at about 2500 "toll centers" out of approximately 6400 central offices in the United States and eastern Canada. Furthermore, the technical developments in toll circuits have led to great increases in the numbers of circuits along a given route. The extension of the use of carrier telephone has increased the capacity of a 40-wire pole line from 30 circuits to 70 circuits. On the heaviest toll routes, moreover, circuits are now provided by means of toll-cable construction, a single cable carrying 200 or 300 circuits. During the past year or two, the growth has been so rapid as to stimulate a very large amount of construction of underground toll conduit routes, providing in many cases for several thousands of telephone circuits on a single route.

General Toll Switching Plan

The conditions outlined above form the background which has made it both possible and important to adopt a new fundamental arrangement for the layout of toll plant and the routing of toll messages. This is called the "General Toll Switching Plan." The purpose of this plan is to provide systematically a basic plant layout designed for the highest practicable standards of service consistent with economy, including speed, accuracy and directness of routing between any two points in the country, and suitable transmission standards. This involves the layout of the plant in such a manner as to limit, so far as it is practicable to do so, the number of switches required for providing a connection between any two telephones and the establishment of standards of design and construction providing satisfactory transmission over any route thus established. The plan is, therefore, of particular value in improving the service conditions of switched toll traffic, that is, traffic requiring the connection of two or more toll circuits.

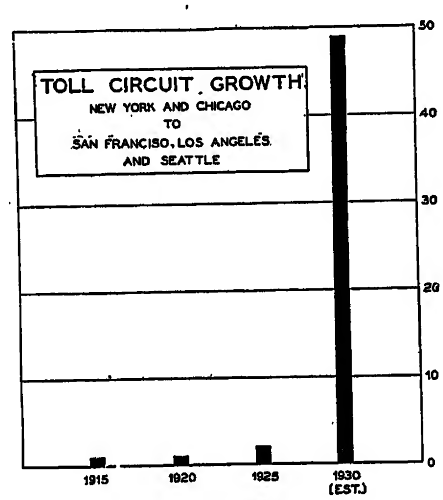
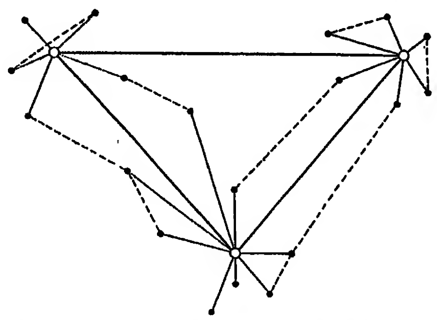


Fig. 4

The general features of the plan will be understood by reference to Figs. 5 and 6. Fig. 5 shows the application of the plan to a limited operating area such, for example, as a state. Within the area are selected a small number of important switching points designated as "primary outlets." Each toll center is connected directly to at least one of these outlets and all primary outlets within the area are directly interconnected. This makes

possible the interconnection of any two toll centers within the area with a maximum of two switches and within the part of the area served by one primary outlet, with a maximum of one intermediate switch.

The primary outlets were selected after a careful study of the present switching and operating conditions



Solid Lines—Fundamental routes of general plan
Dashed lines—Supplementary direct-circuit groups
○ Primary outlet
● Toll center

Fig. 5—General Toll Switching Plan Application in Local Company Area

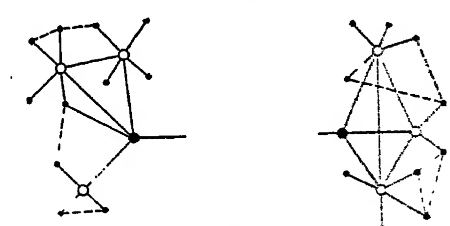
and the probable development of toll traffic within the various areas with a view to obtaining the minimum number of primary outlets capable of handling the traffic economically. The routings provided by the plan are supplemented by direct circuits, or by other routings where the amount of business justifies such additional circuits as indicated by the dashed lines in Fig. 5. In general, the requirement is made that these supplementary routes shall be at least as satisfactory, in regard to both number of switches and transmission, as the routes provided by the fundamental switching plan. However, when the supplementary routes are used only as alternates to a primary routing they may be somewhat less satisfactory in these respects.

The tentative selection of primary outlets is shown in Fig. 7. It is interesting to note that it is found practicable to take care of switching for the 2500 toll centers of the United States and eastern Canada by the establishment of approximately 150 of these as primary outlets.

For handling the business throughout the country eight of the primary outlets are designated as regional centers, which are indicated in Fig. 7. The method of routing calls is indicated by Fig. 6. Each primary outlet is connected with at least one regional center and with as many more as practicable. Each regional center is directly connected to every other regional center in the country. By this means, any one of the primary outlets, which are the 150 most important switching centers in the country, can be connected to any other primary outlet in the country with a maximum of two switches and within the area served by a regional center with a maximum of one intermediate switch. As an illustration of the concentration of switching which results, New York serves as regional center for the entire northeastern section of the United States and eastern Canada.

The extent to which intermediate switching is limited by the application of this plan is indicated by Table I, which shows the maximum number of switches required under the plan between different types of toll centers. It is estimated that the percentage of long-haul messages requiring more than one intermediate switch will, by means of this plan, be reduced by more than 50 per cent.

As an example of the benefit resulting from the adoption of this plan between two remote points, consider a connection which was requested between Pembroke, Ontario, and St. Anthony, Idaho. Under the old routing instructions, such a call required intermediate



Solid lines—Fundamental routes of general plan
Dashed lines—Supplementary direct-circuit groups
● Regional center
○ Primary outlet
● Toll center

Fig. 6—Illustration of Interconnection of Important Switching Offices Throughout Bell System

switches at Ottawa, Toronto, Chicago, Denver, Salt Lake City, Pocatello and Idaho Falls, a total of seven. The chance of establishing such a connection within satisfactory limits of time was, of course, relatively small and the resulting circuit, when established, did not permit the conversation to be held. Under the

TABLE I
GENERAL TOLL SWITCHING PLAN
Maximum Number of Switches

To— / From	Same Regional Area: Regional center	Same Regional Area: Primary outlet	Same Regional Area: Toll center directly connected to regional center	Same Regional Area: Toll center directly connected to primary outlet	Another Regional Area: Regional center	Another Regional Area: Primary outlet	Another Regional Area: Toll center directly connected to regional center	Another Regional Area: Toll center directly connected to primary outlet
Regional center	0	0	0	1	0	1	1	2
Primary outlet	0	1	1	2	1	2	2	3
Toll center (directly connected to regional center)	0	1	1	2	1	2	2	3
Toll center (directly connected to primary outlet)	1	2	2	3	2	3	3	4

general toll switching plan, this call will be routed with switches at Ottawa, New York, Denver, and Pocatello, a reduction of three switches. Furthermore, the circuits involved in this connection will be designed with such transmission standards as to give satisfactory conversation.

The routes provided by the plan for country-wide service are also supplemented by more direct routes of equivalent or better service characteristics in cases where the volume of business is sufficient to make this economical. Furthermore, the routes to regional centers are, in some cases, supplemented by alternate routes through what are called "secondary outlets." These are distinguished from the primary outlets in that they do not necessarily have direct circuit connections to all toll centers in their areas but serve a useful purpose as an alternate route for the toll centers connected to them.

The essential features of the general toll switching plan from the standpoint of the interconnection of the switching offices may be summarized as follows:

Regional Centers. Regional centers are switching offices strategically located to cover the various parts of the country. They are completely interconnected with direct circuits, thus forming the basis of a country-wide toll network.

Primary Outlets. Primary outlets are switching offices having direct circuits to one or more regional centers, each outlet having direct circuits to all toll centers in the area for which it is the primary outlet. Also, each primary outlet is connected to every other outlet within as large an area as is practicable, usually within a State.

Supplementary Offices. 1. Secondary Outlets. Secondary outlets are switching offices having direct circuits to one or more regional centers and are intended primarily to furnish alternate routes for toll centers for reaching the regional centers, thus providing a greater degree of flexibility in the plant. 2. Secondary Switching Points. Secondary switching points are additional switching offices intended to provide routes which are more direct, thus reducing back haul for intra-area business.

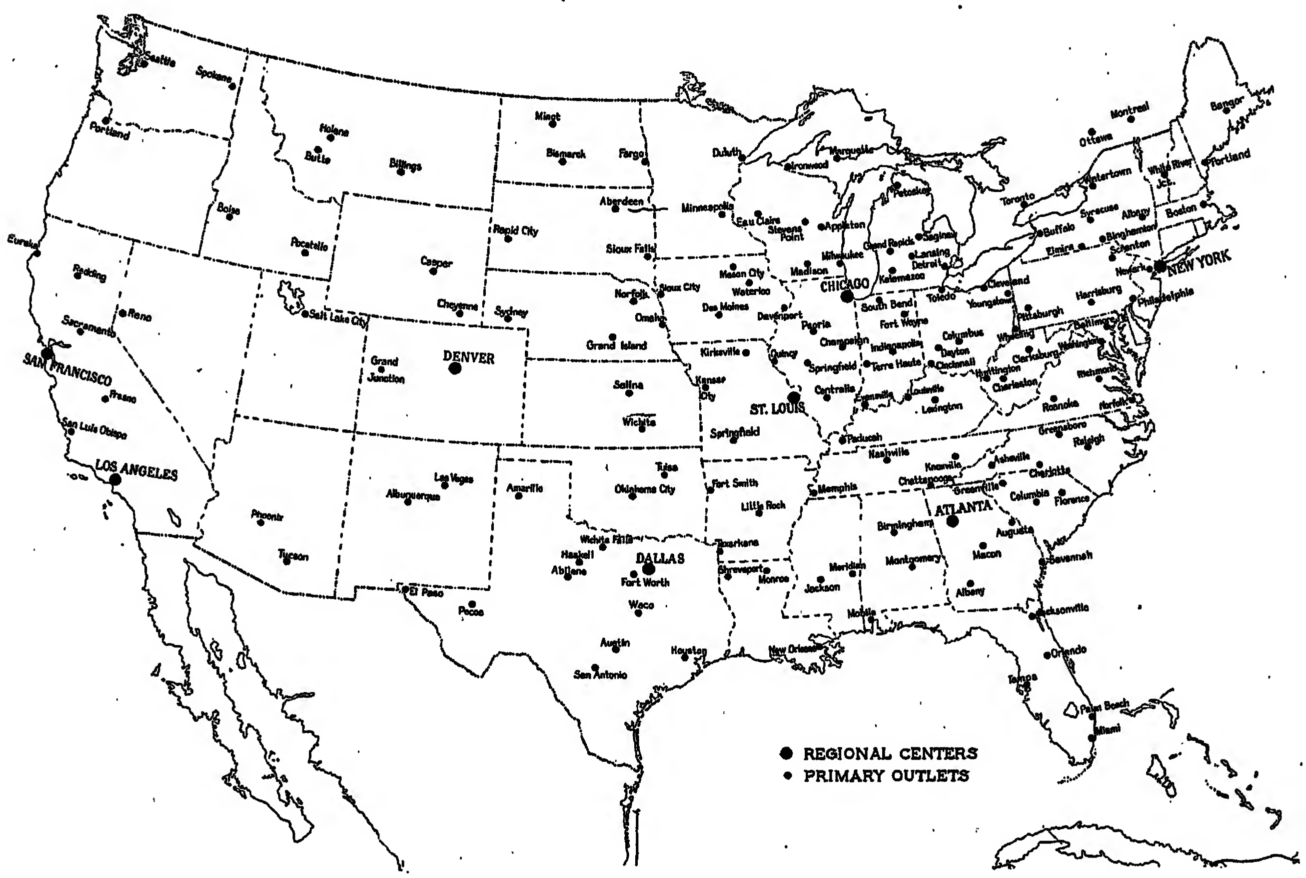


FIG. 7—MAP SHOWING LOCATION OF POINTS TENTATIVELY SELECTED AS REGIONAL CENTERS AND PRIMARY OUTLETS IN UNITED STATES AND CANADA

TRANSMISSION CONSIDERATIONS OF GENERAL TOLL SWITCHING PLAN

An important part of the development of the plan was the determination of proper transmission requirements such that any toll connection established in accordance with the plan would have satisfactory transmission efficiency.

Before the perfection of telephone repeaters the

provision of satisfactory transmission efficiency depended largely upon limiting the total attenuation loss of the complete circuit. At the present time the perfection of repeaters has practically removed that limitation. For example, the attenuation in a New York-Chicago circuit in cable is such that without the use of repeaters the ratio of input power to output power for speech currents transmitted over the circuit would be 10^{46}, while by the use of repeaters at the terminals and at 17 intermediate points the ratio actually is 10.

The removal of the limitation formerly set by circuit attenuation makes possible the increase of the efficiency of circuits to the limit determined by some other characteristic of the circuit. There are various things which under different conditions may determine this limit. One is the effect on transmission of echoes, namely, portions of the speech currents reflected back from the distant end of the circuit or from intermediate points. Another is the distortion due to the building up of greater transmission gain at certain frequencies than at others, which effect may result if repeaters introduce too great an amplification into the circuit. As an extreme case, this might result in a sustained oscillation or singing on the circuit. Other effects which may be important are those of crosstalk between telephone circuits, or of noise induced in the telephone circuits from outside sources, both of which are increased by increasing repeater gains. On the longer connections, echoes are almost always the controlling factor, whereas on the shorter connections, such effects as crosstalk, singing, and noise generally are limiting. A reduction in any of these effects generally involves more expensive types of construction.

The difference between the attenuation loss of the circuit and the total transmission gain introduced into the circuit by repeaters is spoken of as the net equivalent. For long telephone circuits, it is generally economical to provide sufficient repeater gain so that the circuit can be operated at the minimum net equivalent permissible, this minimum equivalent being determined by the transmission factors just mentioned. Therefore, in establishing satisfactory transmission efficiencies for the over-all toll connections in accordance with the toll switching plan, each link must be designed on the basis of the minimum working net equivalent which it will contribute to an over-all connection made up of several circuits switched together.

The establishment of satisfactory and economical transmission requirements for the toll circuits laid out in accordance with the plan involves the following steps:

1. The establishment of satisfactory over-all net transmission equivalents.
2. The coordinated design of all classes of toll circuits, and of the subscribers' circuits, toll switching trunks, and tributary trunks connected to them, in such a way that the desired over-all transmission standards will be given at a minimum total cost when suitable transmission gains are provided by repeaters in the toll circuits and at toll switching points.
3. The economical and satisfactory distribution of transmission gain, permitting all toll circuits to be operated at their minimum working net equivalents when this is desirable.

The over-all transmission equivalents to be given under the plan are based on standards which have heretofore been used for a large part of the toll business but which it has been impracticable to meet in many cases between widely separated points. With the means now available for operating circuits at their minimum working net equivalents, it was found that satisfactory over-all transmission equivalents could be provided under the plan even for the maximum number of switches using standards for the construction of toll circuits very comparable with those already applied to new circuits. Expressed in terms of the transmission reference standard, the plan set up gives a maximum of 25-db. over-all equivalent within one interconnected area (two intermediate switches) and a maximum of 31 db. between any two telephones of the United States and eastern Canada.

In order to determine the most economical distribution of these over-all equivalents, a study was made based upon the estimated total number of toll circuits of each class in 1932 and their distribution by length. It is also necessary to include the corresponding estimates for the plant between the toll office and the subscriber, the loss in this part of the plant being on the average about half of the over-all net equivalent of the connection.

Based upon these estimates, it was possible to determine, by an economic study, the distribution of the over-all minimum net equivalent between these various parts of the circuit which would give minimum total expenses. The toll terminal losses and the minimum net equivalents for toll circuits established in this way are shown in Table II.

TABLE II
GENERAL TOLL SWITCHING PLAN
Transmission Design Data

Classification of toll circuit involved	Minimum working net loss of toll circuit—db.	Maximum via operating equivalent—db.	Transmission margin—db.
Toll center to primary outlet	3.0	4.0	+1.0
Toll center to regional center	3.5	4.0	+0.5
Primary outlet to regional center	3.5	3.0	−0.5
Regional center to regional center	4.0	3.0	−1.0*
Primary outlet to primary outlet	4.0	3.0	−1.0
Toll center to toll center	6.0	6.0	..
Direct toll circuit (for terminal use only)	9.0	..	..
Toll terminal loss	7.0	..	..

*Circuits equipped with echo suppressors may be designed with greater negative margins.

In addition to the circuits involved in multi-switch business, the studies connected with this plan necessarily include circuits used for terminal business only, and others for which switching is limited to a single intermediate switch at points where transmission gain is not required. These circuits are associated with the plan because the portions of the circuit between the toll center and the subscriber are common for these circuits and for circuits directly involved in the general plan. Design standards for these classes of circuits are also shown in Table II.

Provision of Transmission Gain at Intermediate Switching Points

The third step mentioned previously is the determination of the best distribution of repeater gains to permit the individual circuit to be operated by itself or in conjunction with other toll circuits at approximately the minimum net equivalent as determined by the several effects mentioned previously. In so far as the gain of repeaters permanently inserted at intermediate points in a toll circuit is concerned, this is a matter of economical design of the circuit and has been adequately covered in other papers. We are interested here, however, in considering the provision of gain at the intermediate switching points when two toll circuits are connected together.

As indicated previously, echo effects usually control on the longer connections, whereas crosstalk, singing, and noise will usually control on the shorter connections. This is due to the fact that for the great majority of toll circuits the echo effects on individual circuits increase more rapidly with length than do crosstalk and noise. Singing tendencies also increase at a rapid rate with increase in length on two-wire circuits but tend to be independent of length on four-wire cable and carrier telephone circuits which are used to a large extent to provide the circuits between the primary outlets and regional centers and between the regional centers. Furthermore, when two or more toll circuits are connected together, the echo effects of the individual circuits add together almost directly, whereas the effects of crosstalk, singing, and noise increase at a much less rapid rate. The result of these general considerations is that when a toll circuit is switched to another toll circuit, the over-all combination can, in general, be operated at a lower net equivalent as determined by echo effects than the sum of the two circuits when operated individually, in which case the minimum equivalent is determined by the crosstalk, singing, and noise effects. Therefore, it is necessary in the case of connections built up by connecting together a number of toll circuits to introduce repeater gain at the intermediate switching points. If gain were not introduced at intermediate points, it would be necessary in order to obtain the same over-all results on connections involving more than one toll circuit to design and build a considerably more expensive type of toll circuit plant in which the crosstalk, singing, and noise effects would be greatly reduced.

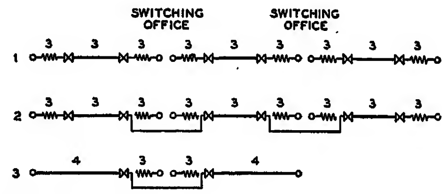
In the past, gain was inserted at intermediate switching points by the use of cord circuit repeaters. These familiar devices consisted of telephone repeaters inserted in the cord circuits and associated by means of double plugs with the toll circuits and with individual balancing networks designed for each toll circuit. By this means intermediate gains of from 4 to 10 db. were inserted at the switching points when connection was made between two toll circuits.

The use of cord circuit repeaters has been an outstanding element in the provision of improved transmission on switched connections. It has, however, some disadvantages which have increased in importance with the increase in transmission efficiency of circuits and with the rapid development of toll business. The routine for inserting the cord circuit repeaters when needed is necessarily somewhat cumbersome, involving considerable expense for operators' labor and for increased use of the toll circuits by operators. Furthermore, under practical conditions it was found not to be possible to insure that the cord circuit repeaters would always be used when required by the routing instructions.

Recent developments in the types of toll circuit have greatly increased the numbers of toll circuits provided with repeaters at their terminals as a part of the most economical circuit design. When such repeaters are available, the desired switching gain can be obtained by making use of the gain available in these repeaters. The great increase in the number of terminal repeaters required for other reasons, important reductions in the cost of repeaters and the savings of operators' labor and circuit time have made it practicable to provide, at certain points, terminal repeaters for every circuit, thus doing away entirely with cord circuit repeaters at these points. With the terminal repeater arrangement, the insertion of transmission gain on switched connections is done automatically by taking out of each circuit on such connections a section of artificial line. This is, of course, the equivalent of increasing the gain of the terminal repeater.

Satisfactory transmission results for all connections under the general toll switching plan involve the insertion of repeater gain on all connections switched at important switching points. This will be carried out by the terminal repeater plan just described. The artificial lines or pads which are cut out of the circuit on switched connections have losses of from 1 to 4 db., depending upon the circumstances of each case. This means that when two toll circuits are switched together, from 2 to 8 db. is automatically subtracted from the connection at each switched point. The arrangement is indicated schematically in Fig. 8. The design of each circuit must, of course, be such that when either end of the circuit is connected to a subscribers' station, the repeater gain at that end will not be greater than

that permissible under the terminating condition, but that when two or more of such circuits are connected together for a long built-up toll connection, the complete circuit will operate at as nearly as is practicable its minimum working net equivalent. While under these conditions the permissible values of the pads associated with the terminal repeaters naturally vary in individual cases, it has been found possible to work out for general use a series of values which should give satis-



Typical transmission data
1. Circuits between switching pad offices in terminal condition
2. Circuits of No. 1 interconnected at switching pad offices
3. Connection between non-pad offices switched at pad office

FIG. 8—DIAGRAM ILLUSTRATING TERMINAL REPEATER-SWITCHING PAD METHOD OF OPERATION—TYPICAL TRANSMISSION DATA

factory results. These are indicated in Fig. 9. It will be noted that these values are such that a circuit switched at both ends to other toll circuits is operated at either 0.5 db. or 1 db. less than its minimum working net equivalent, this deficit being made up by a corresponding margin at the ends of the circuit. For example, by reference to Fig. 9, it will be noted that whereas the design values of the three intermediate links of a five-link connection equate to 11 db., these links will contribute a total loss of only 9 db. On the other hand, the end links will contribute a total of 8 db., whereas their design values equate to only 6 db. The 2-db. marginal deficiency in the intermediate links is compensated for by the 2-db. marginal surplus in the end links. When intermediate links are used as end links in built-up connections, the switching pads at the terminating ends restore the necessary positive margins.

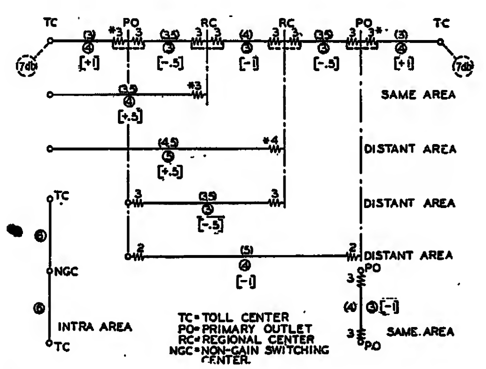
The design of the very long intermediate circuits, such as some of those connecting two regional centers, requires special consideration and treatment to meet the transmission requirements specified. By making use of a fundamental feature of four-wire circuits equipped with echo suppressors and by employing circuits with the highest velocities of propagation for this purpose, these circuits may be designed in practically all cases to contribute not more than the desired operating equivalent for an intermediate link. Four-wire circuits equipped with echo suppressors are unique in that at the longer circuit lengths the increase in minimum net equivalent with further increase in length becomes very slight.

Two general arrangements for removing the switching pads from and restoring them to the toll line circuits are available, depending upon the type of switchboard facilities involved. Either arrangement requires the modification of both the toll line circuit and the switchboard circuits. One method controls the switching pad by a marginal relay in the sleeve of the toll line circuit. In the other arrangement, the pad is under the control of relays operated by battery supplied from a simplex bridge in the connecting circuits.

With the general toll switching plan the number of places in which switching gain is required is greatly limited, being, as pointed out above, a total of about 150 out of 2500 toll centers. This number will be somewhat increased by secondary switching points in which it is found economical to insert switching gain in order to save the back-haul involved in following the routing provided by the plan. However, the net result is that under the toll switching plan the number of points at which switching gain is provided will be materially limited, with corresponding economies.

ESTABLISHING THE PROGRAM OF THE GENERAL TOLL SWITCHING PLAN

The full application of the general toll switching plan involves a large number of individual rearrangements of plant layout, the establishment of certain new circuit groups and the rerouting of a considerable amount of switched business, the conversion of the switching offices to the terminal repeater arrangement, and the modification of the transmission requirements of certain of the



Transmission data
( ) Minimum working net loss
O Operating via equivalent
[ ] Transmission margin
Maximum toll circuit equivalent.........17 db.
Maximum over-all connections..........31 db.
Assumed limiting toll terminal loss....... 7 db.
*Value of pad in terminal links dependent on noise and cross-talk conditions

FIG. 9—GENERAL TOLL SWITCHING PLAN FOR HANDLING SWITCHED TOLL TRAFFIC—TRANSMISSION DATA

circuits. The date at which these rearrangements will be completed is naturally different for different sections of the country and is determined by the regular program of plant additions and rearrangements to take care of increasing business and of needed service improvement. The existence of a comprehensive plan of this sort insures that the program of rearrangements as carried out will be along the lines of greatest economy and maximum improvement in service. The present plans of the telephone companies in the United

States and Canada indicate that the plan as now established will be very closely approximated by the actual plant in the course of about five years.

Future View

Such a plan as has just been discussed is naturally not a static thing but is subject to continual modification to bring it into correspondence with changed conditions. In connection with such changes it is of interest to consider briefly the probable long time trend of the development of the plan.

One possible ultimate development would be the of such an arrangement do not look promising. Furthermore, it would lead to a tremendous congestion of through switching at one point, this congestion going far beyond the limits of economical concentration and leading to serious operating difficulties.

A second, and it is believed more promising, general trend would result from the gradual increase in the number of regional centers as the continued development of business makes this economical. With this growth would come also a continued increase in the number of toll centers connected directly to a regional center. By this process there would be a continued

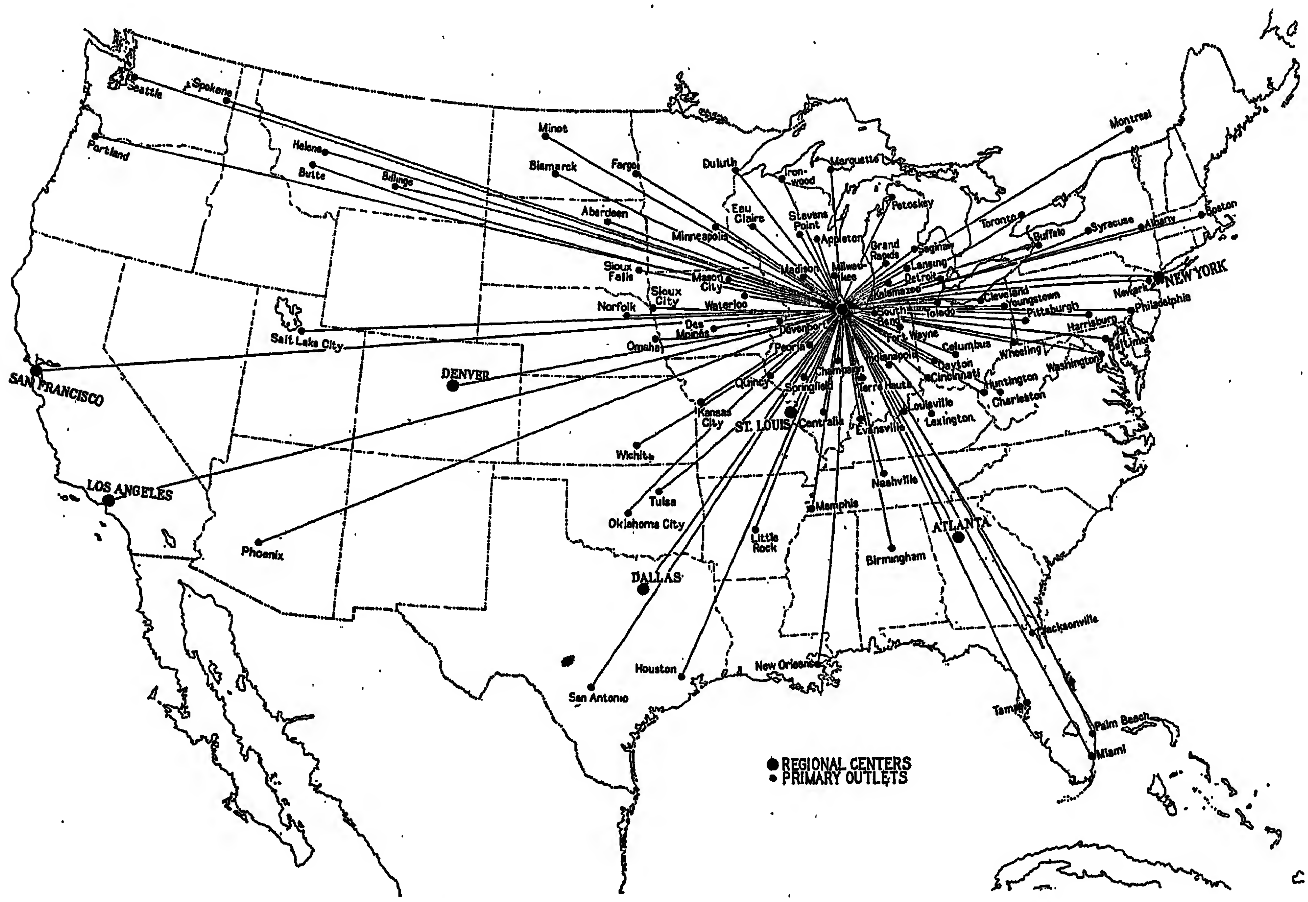


Fig. 10—Map Showing Number of Primary Outlets and Regional Centers Having a Direct Circuit Group to Chicago

increasing connection of primary outlets to a single regional center so that ultimately only one regional center would be necessary. If this were to take place, the regional center would undoubtedly be Chicago. Fig. 10 is interesting as showing the extent to which the primary outlets already are connected directly with Chicago, over one-half of them having such direct connection.

If Chicago ultimately became the only regional center, it would reduce the maximum number of switches to three. It seems evident, however, that such a plan would have many disadvantages. It seems clear that with such an arrangement, numerous secondary regional centers would be necessary to avoid uneconomical back-haul of large amounts of traffic, and the economies growth in the number of toll centers which can be interconnected with a maximum of two intermediate switches, and it is possible that ultimately the primary outlets can drop out of the picture completely, giving a maximum of two intermediate switches for the entire country. While any such outcome is evidently many years away, it seems probable that it is along these lines that the growth in development of the plan should be directed.

Although this direction of development avoids the congestion which would be brought about by the single regional center plan, even under this plan the rapidly growing amount of toll switching to be done in large metropolitan centers offers a very important problem

for the future. Toll switching at these points is rapidly outgrowing the capacity of a single manual switchboard, as the switching of local calls did long ago. Equipment changes are being made which increase this capacity, but they can be only a temporary relief. Looking to the future, an increasing amount of the outgoing traffic will be handled by operators in the local central offices, reaching the toll line over toll tandem trunks. It is evident, however, that the ultimate solution of the problem will involve the use of machine methods for the selection of the toll line by the operators, as is now done in certain segregated toll tandem systems.

The entire trend of recent years is thus to decrease the differences between the handling of exchange messages and of toll messages. At the present time more than 95 per cent of the toll messages are completed while the subscriber remains at the telephone, with speeds of completion only slightly slower than those of exchange messages. Transmission standards, while naturally somewhat better for the shorter distances involved in exchange messages, are, nevertheless, rapidly becoming comparable. The present view of trends for the future is for continuation of this process, perhaps even to the use of similar types of machine equipment at central offices for switching the various classes of messages.

The author gratefully acknowledges the assistance of many of his associates in the preparation of this paper, particularly that of Mr. J. V. Dunn.

Long Telephone Lines in Canada

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Synopsis.—This paper describes the development of long distance telephone facilities in Canada and also outlines certain plans for provision of additional long-haul circuits in the future.

* * * * *

Historical

THIRTY-FIVE years ago a telephone line was constructed from Montreal to Toronto, a distance of 360 mi. At that time technical limitations were such that about 400 mi. was the maximum distance over which good telephone service could be given; hence the above mentioned circuit was then considered to be a very long telephone line.

Since that time the telephone horizon has expanded in a very marked degree, and with this expansion has come a change in ideas as to what constitutes a long telephone circuit.

For many years telephone development in the Dominion of Canada was local in character; service was started in small areas isolated from each other and gradually these areas spread out and became linked with adjacent areas. On account of the great extent of the country and the sparseness of the population, economic difficulties exercised a severe restraint on the construction of the longer links which were required to bridge the gaps between the various settled areas of the country.

Telephone connections between certain of these areas and the Bell System in the United States were early established and this provided a means of communication between different sections of Canada at a time when direct circuits through the Dominion were not economically feasible.

This arrangement possessed marked advantages; first, it provided telephone service between different communities in Canada which would otherwise have been without it; second, it permitted this traffic to grow until it finally reached a point at which it became possible to prove in the building of direct links through Canada.

By the year 1927 the progressive linking together of the various areas throughout which telephone service was being given had reduced the number of these separated territories to four: first, the Maritime Region including the Provinces of Nova Scotia, New Brunswick, and Prince Edward Island; second, the Central Region, including the settled portions of the Provinces of Ontario and Quebec; third, the Western Region, including a large part of the Provinces of Manitoba, Saskatchewan and Alberta; fourth, the Pacific Region, including the southwestern part of the Province of British Columbia. Taking geographical distances into consideration, it may be stated roughly that these regions are located about 1300 mi. apart, reckoning from the middle of one region to the middle of the adjacent region.

Fig. 1 is a map of the Dominion of Canada showing the regions where there is appreciable telephone development.

In the gaps between these regions the nature of the country was unfavorable for telephone line construction; the road connections were incomplete and the settlements were few and far between. Between the western region and the pacific region, the massive ranges of the Rocky Mountains extend for hundreds of miles.

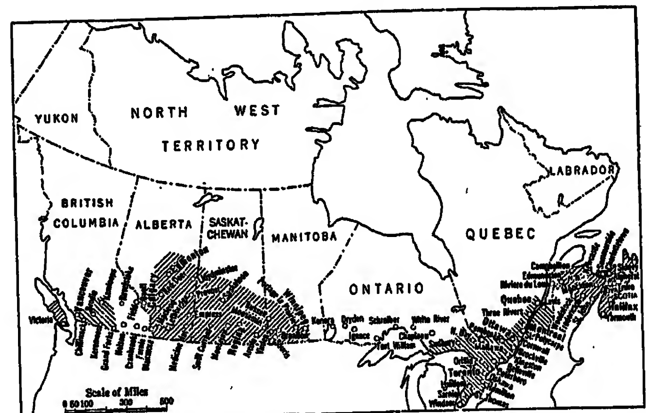

FIG. 1—MAP OF DOMINION OF CANADA SHOWING TELEPHONE DEVELOPMENT

The central and western regions are separated by nearly a thousand miles of very rough and almost uninhabited country. The terrain in this section is very difficult to traverse; there is a continuous succession of rocky hills and ridges which exhibit no regularity of form or direction. Interspersed among these hills are patches of muskeg and small lakes.[2]

Between the maritime region and the central region, there is a long stretch of rough and sparsely populated country.

This last mentioned gap was not entirely without roads and certainly presented less difficulties than either of the other two and in 1928 a pole line was constructed in this section and telephone conductors

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

2. It may be noted that in 1929 certain sections of road in British Columbia which were necessary to bridge various gaps between existing roads were completed, and it is now possible to travel by automobile from Vancouver to Calgary although the route is somewhat circuitous.

There is as yet no highway extending through the section of country lying to the North of Lake Superior.

were erected to provide circuits from Quebec and Montreal to Saint John, N. B.

This left two unbridged gaps, but completing these missing links by means of the erection of pole lines crossing these sections involved formidable problems both in construction and in maintenance of lines after construction.

There existed an alternative method of carrying telephone circuits across these gaps. The main lines of both the Canadian Pacific Railway Company and the Canadian National Railways crossed both of these sections and the telegraph systems of these railways possessed pole lines along the railroad right-of-way. The possibility of making use of one or other of these pole lines to carry telephone circuits was carefully investigated and this plan was found to be practicable.

Negotiations were originated with these railway companies and an arrangement was made with the Canadian Pacific Railway Company for the use of facilities by means of which telephone communication could be established. The necessary telephone repeaters were obtained and placed at suitable locations, and a telephone line was put into operation between Sudbury and Winnipeg in August, 1928; a few months later connections were established by similar means between Vancouver and Calgary.

There is another important factor which had to be taken into consideration; that of ownership of facilities. In the United States, the telephone system of the American Telephone and Telegraph Company and its associated companies extends from coast to coast, whereas in Canada, the telephone service is provided by a number of independent organizations. Prolonged negotiations were necessary in order to arrive at an understanding in this matter, and to evolve a mutually satisfactory plan in accordance with which steps could be taken to inaugurate a system of long-haul telephone circuits of a type suitable to provide universal service between all sections of the Dominion, and to coordinate the construction, maintenance, and operating practises of the various telephone systems to the extent necessary to permit the satisfactory functioning of these inter-regional circuits.

Cooperation between the various telephone systems in Canada was greatly facilitated by the existence of an organization known as the Telephone Association of Canada in which all of the larger telephone systems in the Dominion were represented.

Existing Circuits

At the present time, the long circuits shown in Table I are in operation.

These telephone lines are all two-wire voice frequency circuits. Some of the circuits are located on the same pole line as commercial telegraph circuits for long distances—in one case for approximately 1000 mi. This caused the telephone circuits to be exposed to severe inductive effects from the telegraph currents and special means had to be adopted to avoid undue interference which would have resulted in excessive noise in the telephone circuits.

TABLE I

Circuit	Approximate length of circuit	No. of through line repeaters
Montreal-St. John	620 mi.	4
Montreal-Halifax	890 mi.	6
Toronto-Winnipeg	1285 mi.	9
Calgary-Vancouver	625 mi.	4
Sudbury-Winnipeg	973 mi.	5

The relative interfering effect of a given amount of electric current in conductors situated more or less parallel to the conductors of the telephone circuit depends on several factors. First, there is that of separation; in this case the conductors carrying the disturbing currents were located within a few feet of the telephone circuits.

Second, there is the type of circuit; if the return conductor is distant from the line conductor, the intensity of the magnetic field produced by unit current in the disturbing line is very much greater than the intensity produced by the same current when the return conductor is adjacent to the line conductor. In the case of d-c. telegraph circuits, the return is through the ground and relatively distant from the line conductor. Third, there is the wave shape; if all other conditions are similar, the interference per unit current in the line conductor is proportional to the telephone interference factor of the disturbing current. In the case of high-speed telegraph circuits, the telephone interference factor is very high; for instance, the t. i. f. of the telegraph current in a four-channel multiplex-system operating duplex at 60 words per minute in each direction on each channel is about 900.

The result of all these factors is that the relative interfering effect per unit current is very high. The remedial measures used were; first, the use of a very accurately spaced system of transposing the telephone circuits, and second, the use of low-pass filters in the telegraph circuits. These functioned in such a way as to cut off the high-frequency components in the telegraph currents, and it is these high-frequency components which cause the major part of the interfering effects in the telephone circuits. The insertion of the low-pass filters introduces, in general, only a very negligible effect on telegraph transmission.

These circuits function satisfactorily in providing telephone links between adjacent regions, but the two-wire voice frequency type of telephone circuit has certain inherent limitations which become apparent when attempts are made to make use of this type of facility for establishing very long telephone connections.

These limitations are such that the existing voice frequency open-wire circuits are not entirely satisfactory for all possible connections between alternate regions. In order to provide a suitable grade of

transmission between all points in the various regions in Canada, and particularly for those cases where very long telephone connections will be involved, circuits with high inherent transmission stability and good over-all transmission qualities will be required. As it is not possible to provide direct circuits between all the regions, the circuits provided must be suitable for interconnection by means of switches in order to establish built-up connections. The transmission requirements for the design of these very long telephone circuits are materially more severe than those of much shorter lengths and, as discussed below, in many cases it has been found necessary to introduce telephone facilities of a different type (as regards design

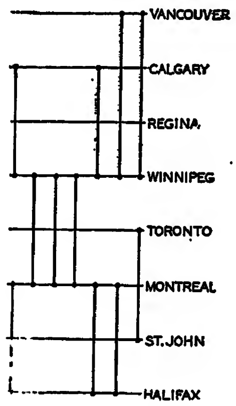


FIG. 2—PROPOSED CIRCUITS IN 1932
This program does not include circuits terminating in adjacent Provinces

and construction) than have been previously used. These include the use of carrier telephone systems superimposed on open-wire lines having special wire configurations, and transmission regulation arrangements.

PROPOSED LONG CIRCUITS

The introduction of the circuits shown in Table I has resulted in a rapid increase in the traffic between adjacent regions and additional facilities are now required to meet the demand for service. The longer haul traffic has also increased to a point where it is now sufficient to warrant the construction of longer direct circuits between various points in Canada.

The results of a traffic study covering the number of calls per day expected in 1932 between certain of the more important points are given below:

1. Toronto-Vancouver.......... 27
2. Winnipeg-Calgary...........156
3. Winnipeg-Vancouver......... 54
4. Montreal-Winnipeg..........107
5. Toronto-St. John........... 36
6. Montreal-Halifax........... 72

In order to provide for these traffic requirements in a manner most suitable from a transmission standpoint, and involving a minimum amount of switching, the fairly comprehensive network of facilities as shown in Table II has been proposed. The engineering work involved in the design and construction of these facilities is now actively under way, and in certain cases, the actual construction work has already commenced.

TABLE II

Circuit	To be completed	Length of circuit	Type
Toronto-Winnipeg.......	1930	1285 mi.	Carrier telephone
Montreal-Winnipeg......	1930	1600 mi.	Carrier telephone
Montreal-Winnipeg......	1931	1600 mi.	Carrier telephone
Winnipeg-Calgary.......	1931	974 mi.	Carrier telephone
Winnipeg-Calgary.......	1931	974 mi.	Voice frequency telephone
Winnipeg-Vancouver....	1931	1820 mi.	Carrier telephone
Calgary-Vancouver	1931	850 mi.	Carrier telephone
Calgary-Vancouver......	1931	850 mi.	Voice frequency telephone

At some later date it is proposed to construct a Toronto-Vancouver circuit. This circuit will be obtained from carrier type facilities and will be 3100 mi. in length.

The circuit layout as proposed in 1932 will provide telephone connections between any two of the main toll centers shown in Fig. 2 with not more than two switches. The cities shown in Fig. 2 are the principal long-distance outlets for each province.

The engineering of these circuits involved the solution of many interesting problems of circuit design and construction methods. Engineering studies of the most economical methods of providing the required plant layout were undertaken in order to establish plans which would be most practicable for the immediate future and would also anticipate the probable requirements for some time to come. The first major problem was that of the determination of the most suitable type of construction for providing the facilities required. This resulted in a consideration of three general plans, the first of which was the construction of new pole lines throughout and the installation on these of a sufficient amount of wire to obtain the circuits required in each section. The second general method was that of stringing wire on existing pole lines with, of course, the building of a small number of new lines where the existing construction could not be used most advantageously. The third possibility was the use of carrier telephone facilities superimposed on open wires on existing pole lines where practicable, and on new construction where such new work was considered justifiable. This last consideration assumed that the carrier circuits would provide for the extensive facilities required and that the open-wire telephone circuits on which the carrier channels were superimposed could be used to advantage in providing for traffic between the shorter haul points; that is, those in the same region and, in some cases, in adjacent regions.

The detailed study of the plans outlined above, taking into account the relative transmission capabilities of the circuits derived under each method and also the relative economies involved, indicated that the most practicable plan would be that of making use of carrier telephone facilities for the longer circuits.

The results of the studies concerning the most desirable construction methods indicated the necessity of employing the best grade of outside plant facilities and wire arrangements, in order to obtain suitable transmission results. As it appeared that ultimately it would be desirable to develop the trans-Canada system on a carrier basis, at least until such time as toll cable would be warranted, and that a maximum number of carrier systems would therefore be required, it was found economical to construct the proposed facilities on the new non-phantomed arrangement. This method involves the abandonment of the phantoms and the spacing of the wires of each pair only eight inches apart. Material benefits in the form of cross-talk and noise reductions are possible with this type of construction. The use of special, improved insulators was also found to be of advantage, in that they would reduce the variations in attenuation under different weather conditions and would thus tend materially to improve the over-all stability of the circuits. This factor is of special importance at carrier frequencies where the variation in attenuation under different weather conditions may be appreciable with the normal types of toll line insulation. The use of the non-phantomed layout of course also indicated the desirability of special transposition arrangements which would provide for the maximum application of carrier facilities.

Survey of Existing Routes

In order to determine the most advantageous routes for these circuits, a comprehensive survey of existing facilities was undertaken. It was necessary to ascertain the most suitable points in each province to be connected to this network and then by means of the data supplied by the survey to determine the most advantageous routes between these points.

The principal factors receiving consideration in this connection were the physical conditions of existing pole lines, the directness of the route between the particular points, the possibility of obtaining suitable locations of repeater points, the expense of necessary changes to the pole line and the existing circuits on the pole line in order to render it capable of long haul circuits. The determination of the condition of the various sections of the existing open-wire leads is normally made on the basis of a pole line inspection. The results of this inspection would indicate those portions of the route which would be suitable without an appreciable amount of reconditioning and would also determine those sections which might require strengthening or replacement due to poor condition, lack of uniformity or susceptibility to interference from power exposures, fire hazards or other external influences. A valuable factor in this survey work would be the possibility of scheduling the various construction items so that the work could be properly coordinated with the provision of the facilities. With the results of this survey and the knowledge of the wire loads to be carried, requirements for the size and character of the poles for the different sections could be determined, having in mind also the relative exposure to weather conditions and the factors of safety desired.

In order to obtain adequate limitation of cross-talk between carrier channels, it is essential to maintain the spacing between successive transposition poles within close limits. This requires an accurate survey of the pole line in order to determine the precise location of each pole.

A further important engineering item is the location of the various repeater points for the carrier-frequency, voice-frequency, and d-c. telegraph facilities. These points are determined by a study of certain transmission features of the circuits, the principal effects receiving consideration being the attenuation, noise, cross-talk and echoes.

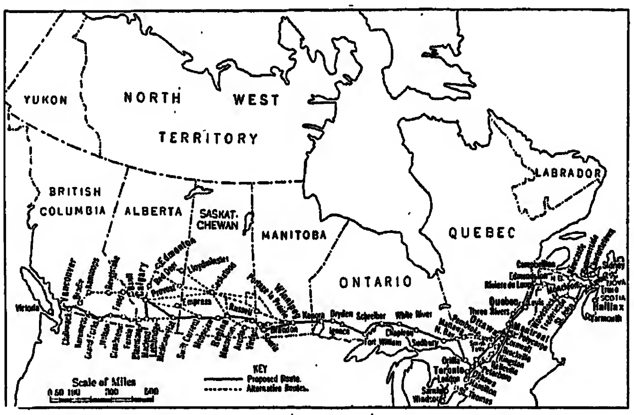


Fig. 3—Proposed Route Trans-Canada Toll System showing Alternate Routes

Other factors, such as the desirability of having repeater points at locations which would be readily accessible, where adequate personnel could be obtained and where the facilities terminated or branched off to other routes, were considered. As the requirements for the location of the repeaters for carrier telephone operation are in general more strict than for voice frequency operation, the selection was made so as to provide the most satisfactory carrier layout. Coordination was then made with the indicated theoretical voice-frequency repeater points. In one or two instances this required the addition of voice frequency repeaters where they would normally not be required.

The matter of alternative routes in case of failure of a particular link was also the subject of considerable study. In some sections only one Canadian route was available; this was the case in the section between North Bay and Winnipeg. (In all cases there was a possibility of routing the calls via United States points during temporary failures due to storm conditions).

The map shown in Fig. 3 shows the route chosen and the proposed alternative routes.

Transmission Maintenance

Due to the greater amounts of apparatus and plant facilities involved and the importance of the greater

inherent transmission variations of very long telephone circuits, the transmission maintenance of suitable over-all transmission standards requires relatively more attention than with shorter transmission systems. In order to provide adequately for these features and to assure the highest degree of efficiency and cooperation in the operation and supervision of these facilities, an extensive investigation was made of the various factors involved, and suitable procedures and arrangements planned accordingly. This investigation included among others, consideration of the following points:

1. The formulation and adoption of uniform transmission maintenance practises.

2. The allocation of responsibility for sectionalized testing and maintenance work and for over-all circuit control.

3. The organization and training of plant personnel.

4. The provision of adequate testing apparatus at all points.

5. The establishment of suitable plant communication systems for maintenance purposes.

Further consideration of the more important points in the establishment of suitable transmission maintenance arrangements are summarized in the following paragraphs:

Experience has shown the necessity of setting up rigid practises for the maintenance of transmission systems of the type proposed in this paper, and the importance of uniform treatment for the respective facilities throughout their entire length. This is of greater importance where the plant and personnel include those of different independent telephone organizations. Plans, therefore, have been made for the preparation of uniform practises which may be applied to all the regions and the establishment of suitable supervisory means for coordinating the over-all maintenance results. These practises provide for the suitable testing and maintenance of each individual part of the circuit, the individual apparatus units and the over-all circuits and systems.

The magnitude of the project and the lengths of the various circuits involved required a careful consideration of the most desirable methods of allocating the responsibilities of the testing and maintenance work so that a minimum of lost circuit time and of unsatisfactory transmission conditions would be incurred. This resulted in the division of the facilities into sectionalized units with one important office in each section designated as the control point. The personnel at this office would be responsible for and control the maintenance work necessary on the toll plant within the limits of its section length. An arrangement of this nature should, in general, simplify the maintenance problem and, furthermore, it would have the advantage of concentrating the supervisory personnel in a limited number of points. In addition, in order to supervise properly the over-all circuit performance, it was found desirable to designate certain of the important terminal offices as master control points. These offices would have the general responsibility of supervising the maintenance of the over-all circuits and would cooperate with the individual section control points in this work.

The necessity for uniformity in the transmission maintenance of the various circuits indicated the desirability of the adoption of arrangements whereby the operating personnel could be suitably trained in an understanding of their responsibilities and in the uniform interpretation and application of maintenance practises. In this connection, consideration has been given to the practicability of regional training courses for carrying out the necessary training work.

The maintenance of satisfactory over-all transmission standards requires the provision at all important points, and particularly at the control points of suitable types of transmission testing apparatus and testboard facilities. The apparatus provided must be suitable for testing quickly the line circuits and transmission systems involved, as well as the individual apparatus units; and the arrangement of the testboard facilities must be such as to allow easy access to the line circuits themselves, or the isolation of the line circuits from the office equipment.

In order to furnish suitable test communication facilities for the use of the plant forces between the control points as well as between these points and the intermediate repeater offices, it will be necessary to provide a special communication system which will allow the various control points to intercommunicate within the range over which they exercise control. A telephone typewriter system with selective control and signaling has been planned as the basic communication system for this purpose.

Another important feature in the provision of suitable testing facilities and arrangements will be the provision of pilot channel equipment associated with each of the carrier telephone systems. These pilot channels will automatically maintain the relative transmission levels of the carrier systems at the intermediate repeater points and at the system terminals within specified transmission limits. A general plan of operations for maintaining the transmission efficiency of these long circuits has been prepared for the consideration of the telephone organizations involved. It is, of course, evident that the success of an undertaking of this magnitude and importance will require the close cooperation of all the systems concerned, and their combined efforts, all directed toward the one accomplishment, that is, the provision of the best grade of telephone service. Up to the present time the progress in the project has been largely the result of the efforts of the Telephone Association of Canada, and it is anticipated that through its continued effort and guidance, this project may be successfully completed and enlarged as future conditions require.

Two-Way Television

Part I—Image Transmission System

BY HERBERT E. IVES,[1] FRANK GRAY,[1] and M. W. BALDWIN[1]

Fellow, A. I. E. E. Non-member Non-member

Synopsis.—*A two-way television system, in combination with a telephone circuit, has been developed and demonstrated and is now in use between the Bell Telephone Laboratories, at 463 West Street, and the American Telephone and Telegraph Company, 195 Broadway. With this system two people can both see and talk to each other. It consists in principle of two television systems of the sort described to the Institute in 1927. Scanning is by the beam method, using disks containing 72 holes, in place of 50 as heretofore. Blue light, to which the photoelectric cells are quite sensitive, is used for scanning, with a resultant minimizing of glare to the eyes. Water-cooled neon lamps are employed to give an image bright enough to be seen without interference from the scanning beam. A frequency band of 40,000 cycles width is required for each of the two television circuits. Synchronization is effected by transmission of a 1275-cycle alternating current controlling special synchronous motors rotating 18 times per second. Speech transmission is by microphone and loud speaker concealed in the television booth so that no telephone instrument interferes with the view of the face.*

* * * * *

Introduction

DURING the past few years, since the physical possibility of television has been established, the chief problems which have received attention have been those of one-way transmission. In particular, the experimental work in radio television has had for its principal goal the broadcasting of television images, which is inherently transmission in one direction. At the time of the initial demonstration of television at Bell Telephone Laboratories in 1927,[2] one part of the demonstration consisted of the transmission to New York of the image of a speaker in Washington simultaneously with the carrying on of a two-way telephone conversation. At that time it was stated that two-way television as a complete adjunct to a two-way telephone conversation was a later possibility. It is the purpose of this paper to describe a two-way television system now set up and in operation between the main offices of the American Telephone and Telegraph Company at 195 Broadway and the Bell Telephone Laboratories at 463 West Street, New York. In principle this consists of two complete television transmitting and receiving sets of the sort used in the 1927 one-way television demonstration. In realizing this duplication of apparatus, however, a number of characteristic special problems arise, and the paper deals chiefly with matters peculiar to two-way as contrasted with one-way television.

Physical Arrangement and Operation

The detailed description of the optical and electrical elements of the two-way television system will be more readily grasped if it is preceded by an account of the general arrangement of the parts and of the method of operation of the system from the standpoint of the user.

The physical arrangement of the two-way television system is shown by the pictorial sketch Fig. 1, and in the illustrations Fig. 2 and Fig. 3. The terminal apparatus is largely concentrated into a booth—the television booth, similar in many respects to the familiar telephone booth,—and a pair of cabinets, which contain the scanning disks and light sources. As in the 1927 demonstration, scanning is performed by the beam method, the scanning beam being derived from an arc lamp whose light passes through a disk furnished with a spiral of holes and thence through a lens on the level of the eyes of the person being scanned. The light reflected from the person's face is picked up by a group

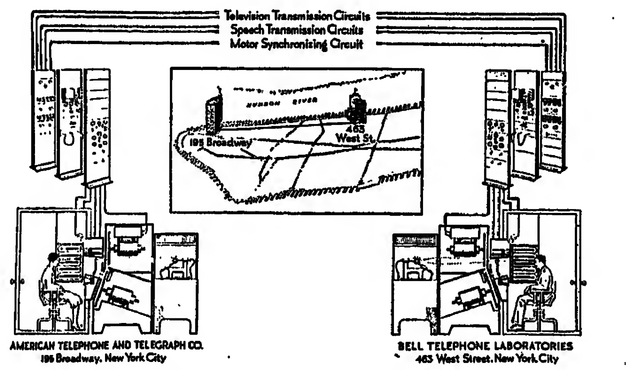


Fig. 1—Pictorial Sketch of Two-Way Television System

of photoelectric cells for subsequent amplification and transmission to the distant point. The signals received from the distant point are translated into an image by means of a neon glow lamp directly behind a second disk driven by a second motor placed below the first and inclined at a slight angle to it. The two disks, which are shown in the center cabinet of Fig. 2, are of slightly different sizes; the upper one 21 in. in diameter and the lower one 30 in. They differ from the disks used in the earlier demonstration in that in place of the 50 spirally arranged holes formerly used, they carry 72 holes whereby the amount of image detail is doubled. While with the earlier "50 line" picture recognizable

1. Members Technical Staff, Bell Telephone Laboratories, New York, N. Y.

2. *Bell System Technical Journal*, October, 1927, pp. 551-652.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

images of a face were obtainable, the aim in this new development was to reproduce the face so clearly that there would be no doubt of recognizability, and so that individual traits and expressions would be unmistakably transmitted. This doubled number of image elements necessarily requires, for the same image repetition frequency (18 per second), twice the transmission band, or approximately 40,000 cycles as against 20,000 for the 1927 image.

The only part of the television apparatus visible to the user is the array of photoelectric cells which are in the television booth behind plates of diffusing glass. In addition to the photoelectric cells and their immediately associated amplifiers, the booth contains a concealed microphone and loud speaker. By means of these, the voice is transmitted to the distant station and received therefrom without the interposition of any visible telephone instrument which could obscure the face.

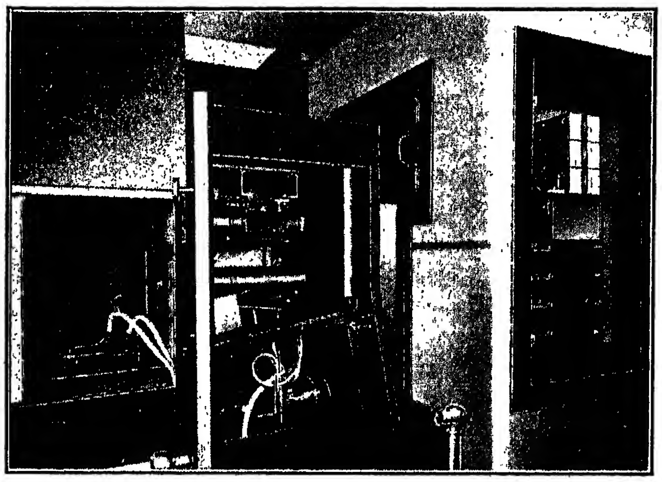


Fig. 2—The Three Major Cabinets of the Television—Telephone Apparatus

From the standpoint of the customer, the operation of the combined television and telephone system is reduced to great simplicity. He enters the booth, closes the door, seats himself in a revolving chair, swings around to face a frame through which the scanning beam reaches his face, and upon seeing the distant person, he talks in a natural tone of voice, and hears the image speak. Conversation is carried on as though across a table.

Optical Problems

Some of the more special of the problems encountered in two-way television are primarily optical in character. The principal one is that of regulating the intensity of the scanning light and of the image which is viewed so that the eye is not annoyed by the scanning beam, or the neon lamp image rendered difficult of observation. It has been necessary for the solution of this problem to reduce the visual intensity of the scanning beam considerably below the value formerly used and to increase considerably the brightness of the neon lamp.

The method adopted consists first, in the use of a scanning light of a color to which the eye is relatively insensitive but to which photoelectric cells can be made highly sensitive. For this purpose blue light has been used, obtained by interposing a blue filter in the path of the arc light beam, and potassium photoelectric cells specially sensitized to blue light and more sensitive than those previously used have been developed. The number of these cells and their area has also been increased over those used in the earlier television apparatus so that the necessary intensity of the scanning beam is decreased.

The second half of the problem, namely that of securing a maximum intensity of the neon lamp, has been attained by the development of water-cooled lamps capable of carrying a high current. The net result of the use of blue light for scanning, of more sensitive photoelectric cells, and of the high efficiency neon lamps is that the user of the apparatus is subjected only to a relatively mild blue light sweeping across his face, which he perceives merely as blue spot of light lying above the incoming image. Fig. 3 shows the interior of the television booth with the frame through which the observer sees the image of the distant person.

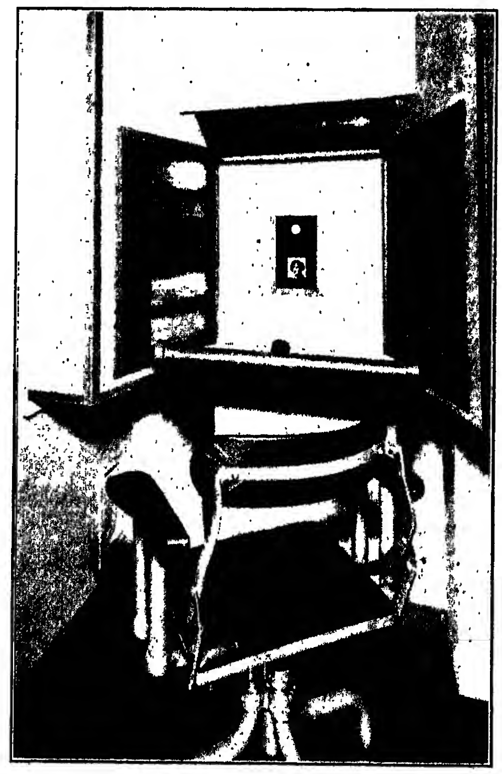


Fig. 3—Interior of the Television Booth

A second optical problem is the arrangement of the photoelectric cells required in order to obtain proper virtual illumination of the observer's face. As we have previously pointed out in discussing the beam scanning

method,[3] the photoelectric cells act as virtual light sources and may be manipulated both as to their size and position like the lights used by a portrait photographer in illuminating the face. In the present case, it is desired to have the whole face illuminated and accordingly photoelectric cells are provided to either side and above. One practical difficulty which is encountered is that eyeglasses, which often cause annoying reflections in photography are similarly operative here. For this reason, it is important that the photoelectric cells be placed as far to either side or above as possible. The banks of photoelectric cells shown in Fig. 3 are accordingly much farther removed from the axis of the booth than were the three cells used in the first demonstration. In the position which has been chosen for the cells, reflections from eyeglasses are not annoying unless the user turns his face considerably to one side or the other.

The number of cells has been so chosen as to secure a good balance of effective illumination from the three sides and it has been found desirable to partly cover the cells on one side in order to aid in the modeling of the face by the production of slight shadows in one direction.

Another optical problem is the illumination of the interior of the booth. There must, of course, be sufficient illumination for the user to locate himself, and it is also desirable that the incoming image and the scanning spot be not seen against an absolutely black background. The illumination of the booth is by orange light, to which the cells are practically insensitive, and so arranged that the walls and floor are well illuminated. In addition to the wall and floor illumination, a small light is provided on the shelf bar in front of the observer so as to cast orange light on the front wall surrounding the viewing frame. This light contributes materially to reducing the glaring effect of the scanning beam, and to the easy visibility of the incoming image.

In addition to the optical features which are visible to the person sitting in the booth, there are very necessary optical elements which have to do with the placing of the outgoing and incoming images. A practical problem which is encountered when customers of various heights use the apparatus is that the scanning beam, if fixed in its position, would strike too high or too low upon many faces. In order to direct the beam up or down as is required, a variable angle prism, consisting of two prisms arranged to rotate in opposite directions, is interposed in the path of the scanning beam. This prism, which lies directly in front of the projection lens used with the upper disk, is shown in Fig. 4 at *P*. Its rotation is controlled by a knob with a numbered dial. The exact position is determined by the operator by reference to a monitoring image which will be described below.

Another optical element, which serves two purposes, is a large convex lens lying between the receiving disk and the observing frame, shown at *L*, Fig. 4. This lens is used to magnify the incoming image to such a size that the image structure is just on the verge of visibility, under which condition the face of the distant person appears as though he were approximately 8 feet away. In addition to acting as a magnifier, this lens serves to position the incoming image to fit the height of the customer. For, by raising or lowering it by means of a knob, the operator, using the information as to the observer's height obtained from the position of the scanning beam, locates the lens so that the virtual image appears in the proper position.

Photoelectric Cells and Associated Circuits

The photoelectric cells used in this apparatus are similar in shape to those used in the first demonstration,

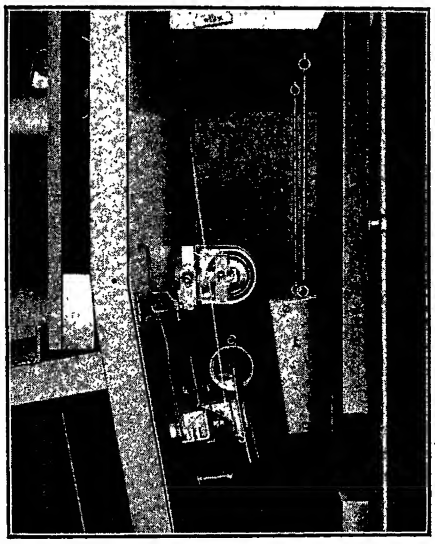


Fig. 4—Optical Means for Controlling Heights of Scanning and Viewing Beams

but somewhat larger. Each cell is twenty inches long and four inches in diameter, giving it an area of approximately eighty square inches for collecting light. The anode is made in the form of a hollow glass rod wound with wire. This construction prevents the electrical oscillations that would otherwise result from mechanical vibrations of the anode. The sensitive cathode consists of a coating, covering the rear wall of the tube, of potassium sensitized with sulphur.[4] This kind of cell is considerably more sensitive than the older type of potassium-hydride cell while still having most of the sensitiveness in the blue region of the spectrum. Fig. 5 shows the response of the photoelectric cells used to the various parts of the spectrum together with the transmission of the blue filter and the brightness of the various parts of the spectrum as evaluated by the human eye. The very great efficiency of the photoelectric cells and the inefficiency of the eye to the light used are apparent.

3. *Jnl. Optical Soc. of America*, March, 1928, p. 177.

4. A. R. Olpin; *Phy. Rev.* 33, 1081, (1929).

To amplify the photoelectric current, the cells are filled with argon at a low pressure. Photoelectrons passing from the sensitive film to the anode ionize the gas atoms along their paths and thus cause a greater flow of current. The ionization of the gas does not, however, instantaneously follow sudden variations of the true photoelectric emission from the sensitive film, that is, there is a time lag in the ionization of the gas and in the disappearance of ionization. This lag results in a

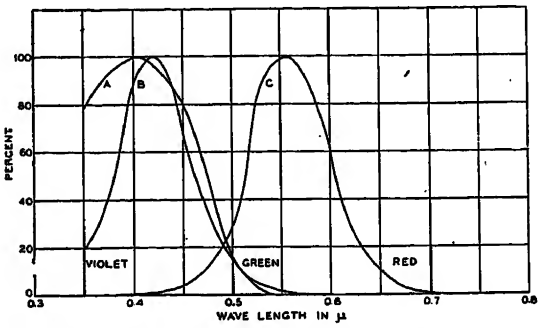


FIG. 5—*A* RELATIVE OPTICAL TRANSMISSION OF THE BLUE FILTER THROUGH WHICH THE SCANNING BEAM PASSES

B RELATIVE SENSITIVITY OF THE PHOTOELECTRIC CELLS TO VARIOUS PARTS OF THE SPECTRUM

C RELATIVE SENSITIVITY OF THE EYE TO VARIOUS PARTS OF THE SPECTRUM

relative loss and phase shift of the high-frequency components of a television signal with respect to the low-frequency components which become serious in the wider frequency range utilized in the 72 line image. The relative loss in output from a single large photoelectric cell at high frequencies is shown in decibels by curve *A* of Fig. 6.

In the television booth, the twelve large cells mounted in the walls of the booth present an area of approximately seven square feet to collect light reflected from a

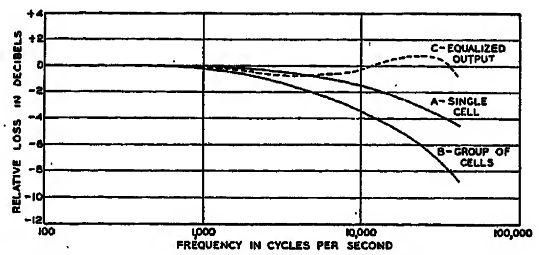


FIG. 6—LOSS IN RESPONSE OF PHOTOELECTRIC CELLS AT HIGH FREQUENCIES

subject. To secure the desired effective illumination, the cells are mounted in three groups, comprising a group of five cells in each of the two side walls of the booth and a group of two cells in the sloping front wall above the subject. The twelve cells are enclosed in a large sheet copper box, provided with doors to each group. The cells of each group are connected in parallel through the input resistance of a two stage resistance-capacity coupled amplifier similar to those previously used. This raises the level of the signal to such a point that the output of the three amplifiers may be carried through shielded leads and connected in parallel to a common amplifier.

The metal anodes and lead wires of the cells in parallel in any one group give an appreciable capacity to ground, which results in a further loss in amplitude and phase shift of the high-frequency components of the signal. The combined loss introduced by ionization of the gas in the cells and by capacity to ground is shown by curve *B* of Fig. 6. This combined loss is equalized by an interstage amplifier coupling, Fig. 7. The equalized output from the photoelectric cells is shown by curve *C*, Fig. 6.

TWO-WAY IMAGE SIGNAL AMPLIFIERS

The vacuum tube system used to amplify the photoelectric cell currents in two-way television is patterned closely after that used previously in one-way television, and the description here will be confined chiefly to novel features. These new features are necessary to take care of the doubled frequency band which results when the scanning is done with a 72-hole disk rather than with a 50-hole one, and to provide sufficient

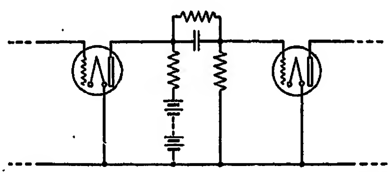


FIG. 7—SCHEMATIC OF INTERSTAGE AMPLIFIER COUPLING TO EQUALIZE FOR THE HIGH FREQUENCY LOSSES IN THE PHOTO-ELECTRIC CELLS

power to operate the high intensity neon lamp which is essential to two-way television. Certain other new features have been introduced in order to simplify the apparatus and to reduce the maintenance required to keep it in good working condition.

The vacuum tubes which operate at low energy levels are the so-called "peanut" type, chosen because of their freedom from microphonic action and their low inter-electrode capacities. Protection against mechanical and acoustical interference is secured by mounting these tubes in balsa wood cylinders which are loaded with lead rings and cushioned in sponge rubber. The tubes are electrically connected in cascade by means of resistance-capacity coupling, so that the whole amplifier system is stable over long periods of time and is also uniformly efficient over the required frequency band. Grid bias for the small tubes is supplied by the potential drop across a resistance in the filament circuit; the power requirements for the low level stages of the amplifier are filled by 6-volt filament batteries and 135-volt plate batteries, all located externally where they can be checked and replaced conveniently.

The amplifier system is divided into units of convenient size as shown in Fig. 8. Associated with each of

the three banks of photoelectric cells is a two-stage unit known as the photoelectric cell amplifier; the combined output of these three units is carried to a four-stage unit known as the intermediate amplifier, output of which is of sufficiently high level to be carried outside the copper cell cabinet to the three-stage transmitting power amplifier on the relay rack. A four-stage unit known as the receiving power amplifier is also on the relay rack, and serves to amplify the signal from the other station to a level which will yield an image of satisfactory contrast when it is translated into a light variation by means of the neon lamp. The final stage of this amplifier consists of two special 250-watt tubes in parallel. These large tubes are used because their plate impedance is of the same order of magnitude as the impedance of the neon lamp, and because they will supply the necessary direct current to the neon lamp without overheating.

Fig. 8 also shows what may be termed a voltage level diagram for the whole system. Ordinates on this

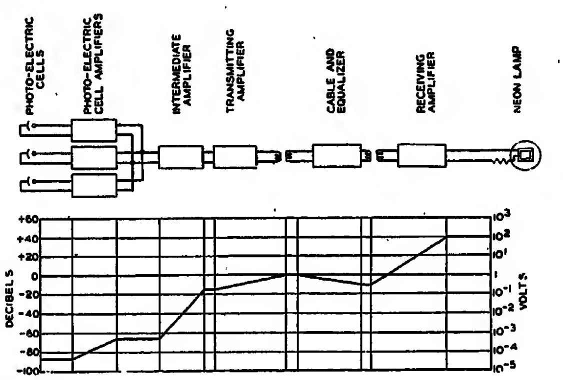


Fig. 8—Schematic Diagram of the Complete Television Channel and the Relative Voltage Levels of the Signal Along the Channel

diagram represent voltage amplitudes at the junctions between units of the system, and by themselves tell nothing at all about the power conditions in the system, since the impedances are not specified. It is interesting to observe that the signal voltage produced by the three banks of photoelectric cells has an effective value of about 50 microvolts across the 50,000 ohm input resistance; the transmitting amplifier delivers about 1 volt to the 125 ohm cable circuit, and the receiving amplifier delivers about 100 volts to the 1000 ohm neon lamp circuit. The signal current through the neon lamp has an effective value about a thousand million times greater than that of the current variation in one of the photoelectric cells.

The most outstanding contribution to the development of television amplifiers is the combination of output and input transformers whose transmission characteristics are shown in Fig. 9, *A*, and whose impedance characteristics are shown in Fig. 9, *B* and *C*. The exceptionally wide frequency range, corresponding to a ratio of limiting frequencies of 5000 to 1, transmitted by these transformers is due largely to the use of chrome permalloy, a recently developed core material having very high permeability. The improved characteristics are also the result of refinements in design which involve the use of adjusted capacities and resistances to control the characteristics at the higher frequencies. Due to the fact that each terminated transformer looks like a resistance of 125 ohms over practically the entire frequency range of the image signal, it makes no difference in the form of the over-all voltage amplification characteristic of the circuit whether the transformers are connected together

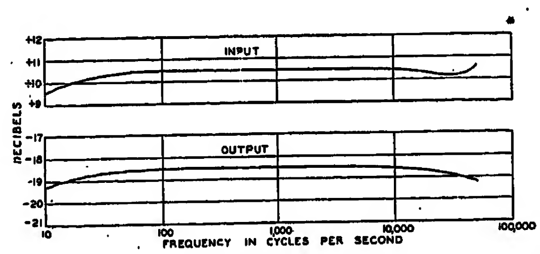


Fig. 9A—Voltage Ratio Characteristics of W-7879 Input Transformer and W-7880 Output Transformers, Each Connected Between Its Rated Impedance

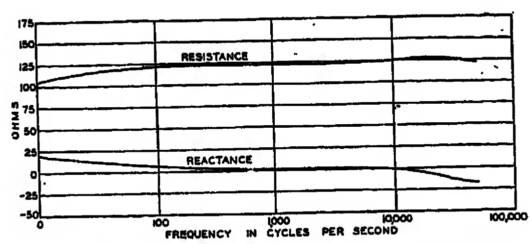


Fig. 9B—Impedance Characteristic of W-7880 Output Transformer with 1765 Ohm Resistance Load

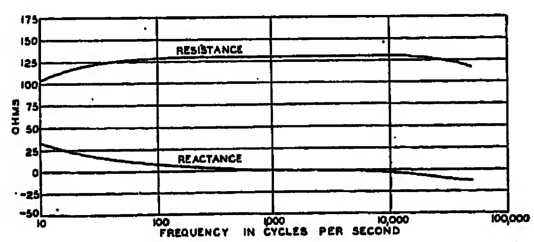


Fig. 9C—Impedance Characteristic of W-7879 Input Transformer with 20 Mmf. Capacity Load

directly or by means of the equalized cable circuit whose characteristic is shown in Fig. 10. Advantage of this circumstance is taken in providing switching means whereby each transmitting amplifier may be connected through a resistance pad to its local receiving amplifier, enabling a person to see his own image in the television booth, which is a convenience in making apparatus adjustments.

Transformers of this type must be carefully protected against magnetizing forces which might cause polarization of the core material. In order to keep the plate current of the final tube of the transmitting power amplifier from flowing through the winding of the out-

put transformer, the transformer winding is shunted by a battery and a resistance in series. The resistance is made high, so that the transmission loss due to bridging it across the circuit is small; the voltage of the battery is made equal to the potential drop across the resistance due to the plate current of the tube, so that the average voltage across both the battery and resistance, and hence across the transformer winding, is zero.

A vacuum thermocouple is connected in series with the line winding of the output transformer, serving as a level indicator for the transmitting amplifier. The level indicator for the receiving amplifier is a vacuum thermocouple in series with the grid resistance of the two 250-watt tubes.

The electrical control panels associated with one terminal of the television apparatus are shown in Fig. 11.

Transmission Circuits

Two special requirements for the two-way television transmission circuits are to be emphasized. The first, which has already been referred to, is the wide frequency transmission band, from 18 cycles to 40,000

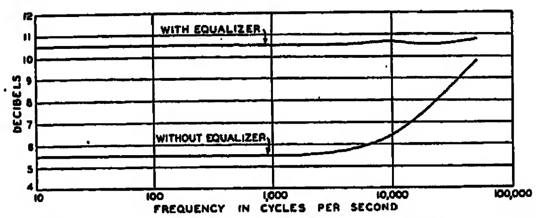


Fig. 10—Insertion Loss Characteristic of Cable Circuits which Transmit the Image Signal, Measured Between 125 Ohm Resistances

cycles, which must have a high degree of uniformity of transmission efficiency and freedom from phase distortion. The second is the necessity for *two* circuits for the television images. This arises from the fact that the two parties to the conversation must both see and be seen at all times. There can be no interruption of one face by the other, comparable with the alternation of the role of speaker and listener in telephony which permits the use of a single circuit for ordinary speech communication.

The terminal stations of the two-way television system are connected by eight underground circuits, each consisting of 13,032 ft. of No. 19 gage and 390 ft. of No. 22 gage non-loaded cable. Two circuits are used for transmitting the image signals, two for the accompanying speech, one for the synchronizing current, two are used as order wires, and one is kept as a spare. All of the circuits have identical transmission characteristics, but equalization is necessary only on the two which carry the image signals. Fig. 10 shows the insertion loss characteristic of each circuit, and also shows the insertion loss characteristic of the image circuits when the image line equalizers are included.

Although the distance between the stations is small the requirements of the television system from the standpoint of freedom from noise and other interference require that considerable care be given to the selection of the cable circuits used. All terminal connections are made through balanced repeating coils or transformers so that all of the circuits are balanced to ground. Also, in order to insure that the crosstalk between the various channels be unnoticeable the terminal equip-

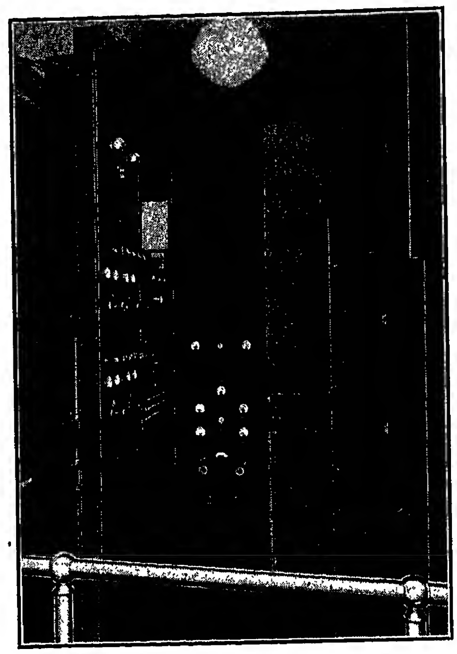


Fig. 11—Control Apparatus Panels Associated with One Terminal of the Television Apparatus

ment is so adjusted that approximately the same amount of power is transmitted by each circuit.

Neon Lamps and Associated Circuits

After amplification, the received television signal is impressed on the grids of two power tubes in parallel to

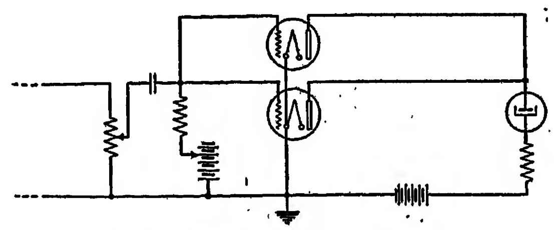


Fig. 12—Schematic of Neon Lamp Circuit

furnish current for a neon receiving lamp. The terminal lamp circuit is shown in Fig. 12. The grid bias of the two power tubes is varied by the operator to control the d-c. plate current, which replaces the original d-c. signal component suppressed at the sending end. The quality of the reproduced image is determined by the operator's control over the relative levels of the incoming a-c. signal and the restored d-c. current.

The television current from the power tubes is translated back into light by a water-cooled neon

lamp designed to operate on a large current. The structural details of the lamp are shown in Fig. 13. Heavy metal bands attach the rectangular cathode to a hollow glass stem occupying the central portion of the tube. Water from a small circulating pump flows continuously through the glass stem and cools the cathode by thermal conduction through the metal bands. To reduce sputtering of the cathode and consequent blackening of the glass walls, the front surface of the cathode is coated with beryllium. This

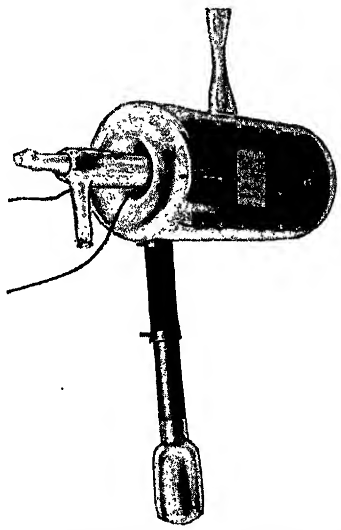


Fig. 13—Water-Cooled Neon Lamp

metal resists the disintegrating action of the glow discharge very satisfactorily and gives the lamp a prolonged life. Other metal surfaces in the tube are shielded from the discharge by mica plates; and the discharge passes from the frame-like anode to the front surface of the cathode, covering it with a brilliant layer of uniform cathode glow.

Pure neon in a plate type of lamp gives a very inferior reproduction of an image. The impedance of the lamp is relatively high and comprises both a resistance and a reactance which vary with frequency. The variation in the impedance causes a relative loss in the frequency components of the signal and also introduces spurious phase shifts. In addition, pure neon has an after-glow; the gas continues to glow for an appreciable time after current ceases to flow. This after-glow casts spurious bands of illumination out to one side of the brighter image details.

A small amount of hydrogen in the neon prevents such an after-glow; and at the same time improves the circuit characteristics of the lamp. The total impedance of the lamp is lower, making it a less influential part of the lamp circuit; and the resistance and reactance vary in such a manner that the phase shift is more nearly proportional to frequency, (a phase shift proportional to frequency causes no distortion in the reproduction of an image). Other active gases may be used with the neon to improve the operation of a television lamp, but one or two per cent of hydrogen is most satisfactory.

Since hydrogen is absorbed by the electrodes in a glow discharge, it slowly disappears from the neon during operation of the lamp. For this reason the lamp is provided with a small side reservoir of hydrogen. The lamp and the reservoir carry porous plugs immersed in a pool of mercury; and a flexible rubber connection permits the two plugs to be brought into contact at will. Minute quantities of hydrogen may be introduced into the lamp by simply bringing the two plugs into contact for a short time.

Even with this improvement the circuit characteristics of a lamp are not ideal. With power tubes it is usually desirable to include a fixed resistance in series with the lamp to prevent semi-arcing conditions. Such a resistance also makes the lamp a less influential fraction of the total circuit impedance.

Optical Monitoring Systems

In order to insure that the incoming and outgoing images are properly positioned, no matter what the stature of the person sitting in the booth, and that the images shall be of proper quality, it is essential to have some means for the operator to observe and adjust these images. The optical monitoring system provided consists of an outgoing monitor and means for adjusting the scanning beam, and an incoming monitor and means for adjusting the position of the viewing lens to suit the height of the sitter.

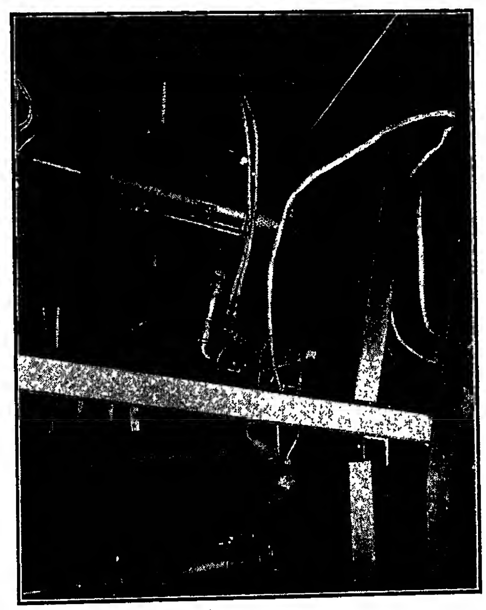


Fig. 14—Sending and Receiving Disks, with Neon Lamps and Optical Arrangements for Image Monitoring

The outgoing monitoring system is the same as that used in the one-way television apparatus which has already been described. A small neon lamp (Fig. 14, at bottom of top disk) is placed behind the sending disk but displaced several frames from the aperture

through which the arc lamp beam passes. By continuing the spiral of holes part way around it is possible to see the complete image from the auxiliary neon lamp, to which the outgoing signals are also supplied. In order to see this monitoring lamp from the operator's position, a right-angle prism and a magnifying lens are placed in front of the disk and the image is observed through an opening in the side of the motor cabinet. The task of the operator is to direct the scanning beam up or down by means of the variable angle prism until the face of the person in the booth is centrally located. This adjustment is facilitated by a wire which passes across the image and is placed at the height at which the customer's eyes should appear.

The height of the observer's eyes is an indication of the position which should be taken by the large magnifying lens *L*, and the operator, after having properly placed the scanning beam, reads the scale on the variable angle prism dial, and then sets the magnifying lens by turning its controlling knob to the same number. When both adjustments are complete, the person in the booth will not only be properly scanned but will be in the best position to see the image.

In order to monitor the incoming image, an optical arrangement is adopted by means of which light from the water-cooled neon lamp is taken off at the side and reflected through the disk and thence reflected again, as shown in Fig. 14, (top of bottom disk), through a second, lower, observing hole on the side of the motor cabinet. Because of the small area of the side view of the neon lamp, a lens system is inserted which focuses the image of the lamp at the place to be occupied by the pupil of the operator's eye. When the eye is properly placed, the whole of the lens area is seen filled with light and exhibits the incoming image.

In addition to the monitoring means just described, an additional view of the incoming image is provided by means of a 45-deg. mirror which is carried on the back of a movable shutter which is shown at *S* in Fig. 4. This shutter carries an illuminated sign on the side turned to the customer with the inscription, "Watch this space for television image." The shutter with its sign covers the image until the adjustments just described are made, when it is dropped out of sight. While it is in place, the operator is provided with an additional monitoring image reflected from the 45-deg. mirror. This view is, of course, in every respect identical with that which the customer sees.

The function of the incoming monitoring system is primarily to enable the operator to set the electrical controls to give the proper quality of image. He also has another task which is that of properly framing the image. This he can do by turning the framing handle, which is described elsewhere, while watching the image from the mirror. The framing operation is preferably performed not on a person sitting in the booth but upon some suitable object such as a mirror located upon the rear door of the booth. In order to make this framing adjustment, the operators at the two terminals set their scanning beam dials to predetermined positions such that the scanning beams place the framing mirrors at the lower edge of the scanning rectangles; the phases of the incoming disks are then shifted until the images of the mirrors are seen properly located in the incoming monitors.

Signaling System

In order to coordinate operations at the two terminal stations, an order wire system is provided. There are four telephone sets at each station; one on the attendant's desk in the ante-room, one concealed inside the television booth, one in the control room, and one at the control panels for the technical operator, who operates the small switchboard which is part of the system. Two of the underground cable circuits connect the two switchboards, so that there may be not more than two separate conversations between stations at one time. Ringing is accomplished by means of standard 20-cycle ringing current furnished by the telephone company.

During a demonstration, the attendants' telephones are connected permanently over one of the cable circuits. To relieve the operators of the duty of ringing each time the attendants wish to communicate, a push button and buzzer are provided at each attendant's desk, operated by the standard ringing currents simplexed on the synchronizing circuit. This arrangement leaves the operators free to manipulate the television apparatus.

The two order wire circuits are each simplexed to provide two additional circuits which operate signal lamps indicating to both operators when either chair in the television booths is occupied and turned in position.

Conclusion

The primary objects in developing and installing the two-way television system have been two. The first was to obtain information on the value of the addition of sight to sound in person to person communication over considerable distances. The second was to learn the nature of the apparatus and operating problems which are involved in a complete television-telephone service. While the installation is entirely experimental, it is being maintained in practically continuous operation for demonstration to employees and guests of the telephone company, and interesting data are being gathered on all aspects of the problem.

It may be said without fear of contradiction that the pleasure and satisfaction of a telephone conversation are enhanced by the ability of the participants to see each other. This is, of course, more evident where there is a strong emotional factor, as in the case of close friends or members of the same family, particularly if these have not been seen for some time.

Were the television apparatus and required line facilities of extreme simplicity and cheapness it would be

sate to predict a demand for its early use. At the present time, however, the terminal apparatus is complex and bulky, and requires the services of trained engineers to maintain and operate it. In addition to the cost of the terminal apparatus there is the unescapable item of a many-fold greater transmission channel cost. Because of the wide transmission bands required for the television images, the inherent necessity for a television channel in each direction, and the extra channels for synchronizing and signaling, the total transmission facilities used in this demonstration are those which could, according to current practise, carry about fifteen ordinary telephone conversations. It is to be expected, of course, that development work will result in some increase in the efficiency of the transmitting channels and in simplifications of the terminal apparatus. It is conceivable, therefore, that our present conception of the cost of the whole system may ultimately be materially changed.

PART II—SYNCHRONIZATION SYSTEM

By H. M. Stoller[5]

Member, A. I. E. E.

General Requirements

Television transmission requires not only synchronization of the transmitting and receiving equipment but

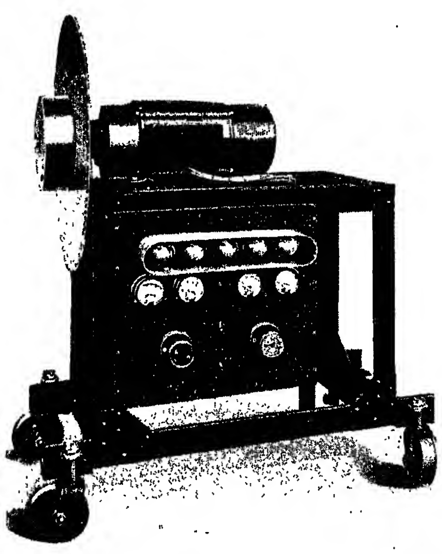


Fig. 15—New Television Motor and Vacuum Tube Control Circuit

such synchronization must be held to a narrow phase angle so that the scanning disks at the transmitting and receiving end will never depart more than a small fraction of a picture frame width from the desired position.[6] In the 1927 demonstration, 2125-cycle synchronous motors were employed with supplementary d-c. motors to facilitate starting. This plan required the use of vacuum tube amplifiers of large size in order to supply sufficient power to the synchronous motors.

Such high-frequency synchronous motors, however, are inefficient and expensive, so that when designing the new system it was desired to solve the problem of synchronization with simpler and cheaper equipment and in a manner which would require less attention in starting. It was particularly desired to employ a motor which could be operated directly from the 110-

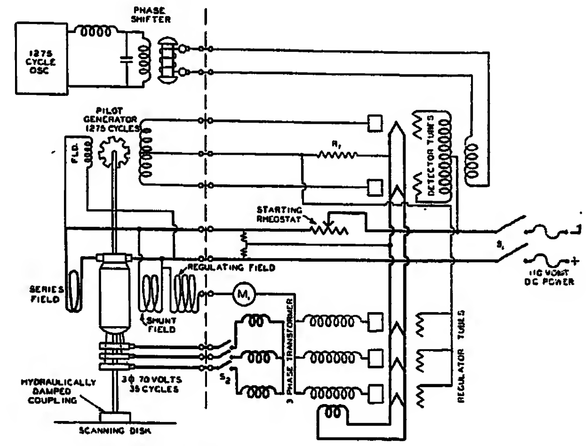


Fig. 16—Schematic Diagram of Control Circuit

volt lighting circuit without any auxiliary *A*, *B*, or *C* batteries for the control equipment.

Description of Motor

Fig. 15 shows a photograph of the new television motor and its associated control equipment.

The motor is a four-pole, compound-wound, d-c. motor with the following special features added:

1. An auxiliary regulating field, the current through which is controlled by the vacuum tube regulator.
2. A damping winding on the face of the field poles to prevent the field flux from shifting (Fig. 17).
3. Three slip rings are provided at points 120 electrical degrees apart for furnishing three-phase power to supply plate and filament voltage for the regulating circuit.
4. A pilot generator of the inductor type is built into the motor frame and delivers a frequency proportional to the motor speed for actuating the control circuit.
5. A hydraulically damped coupling is provided between the motor shaft and the scanning disk. (Fig. 18).

The motor frame was made from a standard 36 tooth stator punching by cutting out three teeth per pole, thus forming four polar areas of six teeth each. The shunt, series, and regulating fields enclose the entire polar areas. The damping winding consists of insulated closed turns of heavy copper wire distributed over the pole faces in the slots as shown in Fig. 17. It will be noted that this damping winding has no effect upon the flux through the poles as long as the flux density over the polar surface does not shift. In other words, the damping winding permits the total flux of the motor to

5. Apparatus Development Dept., Bell Telephone Laboratories, New York, N. Y.

6. These requirements are more fully discussed in a previous paper of the A. I. E. E. Journal, Vol. 46, p. 940, 1927.

increase or decrease as required by the regulating circuit but will oppose any tendency of the flux to shift back and forth across the pole face. As will be explained later on, this feature is essential in order to prevent hunting or instability of the image.

The hydraulically damped coupling between the motor shaft and the scanning disk is also essential in order to avoid hunting. It employs flexible metal bellows filled with oil and connected by a small pipe

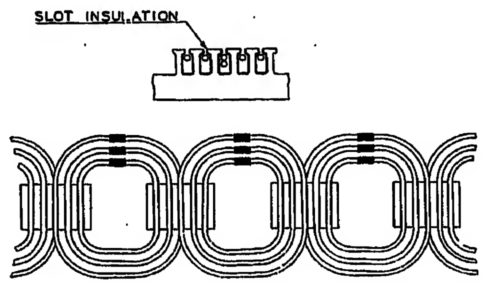


FIG. 17—DAMPING WINDING PREVENTING SHIFTING OF FIELD FLUX

equipped with a needle valve for adjusting the amount of damping. Fig. 18 shows its construction. The scanning disk itself is centered on a ball bearing which allows the disk to rotate with respect to the shaft within approximately ± 5 degrees mechanical movement.

CONTROL CIRCUIT

Fig. 16 shows a schematic diagram of the control circuit. When the motor is operating at full speed the

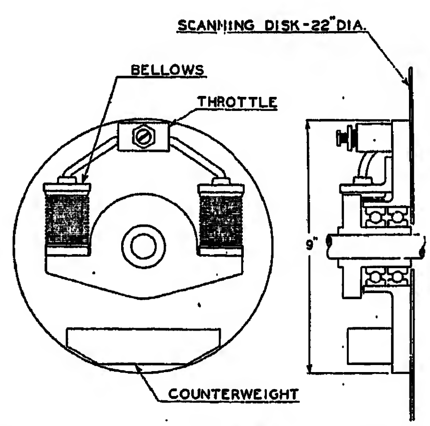


FIG. 18—HYDRAULICALLY DAMPED COUPLING TO PREVENT HUNTING OF MOTOR

pilot generator delivers approximately 1 watt of power at 300 volts, 1275 cycles to the plates of a pair of push-pull detector tubes. The grids of these tubes are supplied with an e. m. f. of the same frequency from an oscillator or other source of power having a sufficiently constant frequency. The amount of power required for this grid circuit is only a few thousandths of a watt. The detector tubes rectify the plate voltage producing a potential drop across the coupling resistance R_1. If the plate and grid voltages are in phase, so that the grids of the tubes are positive at the same instant that the plates are positive, the plate current will be a maximum. If the grid voltage is negative when the plate voltage is positive the plate current is practically zero, so that the magnitude of this current is a function of the phase relationship between the grid and plate voltages as shown in Fig. 19.

The voltage drop across the coupling resistance R_1 is applied to the grid circuits of three regulator tubes. These tubes derive their plate voltage supply from a three-phase transformer fed with power from the three slip rings provided on the motor. These tubes act as a rectifier whose output is controlled by the potential impressed upon the grids from the coupling resistance R_1. The current of the regulator tubes is passed through the regulating field provided on the motor. This field is in a direction to aid the shunt field and series fields of the motor.

The operation of the circuit is as follows: In starting switch S_1 is closed which applies direct current to the shunt field and armature circuits of the motor. The motor accelerates as an ordinary compound wound motor. Switch S_2 is then closed applying three-phase

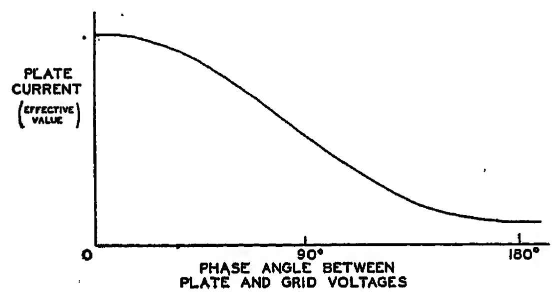


FIG. 19—PHASE DETECTOR TUBE CHARACTERISTIC

power from the slip rings of the motor to the transformer. As the speed of the motor approaches the operating point, the beat frequency between the pilot generator and the oscillator will cause beats in the current through the regulating field which are visible on the meter M_1. Let us assume that the field rheostat has been previously adjusted so that with the shunt field alone the motor will tend to run slightly over the desired operating speed. When the exact operating speed is obtained, the beat frequency in the regulating field will be zero and as the motor tends to accelerate, the phase relationship between the pilot generator and the oscillator will reach a point tending to give maximum strength to the regulating field. When this point is reached, the acceleration of the motor will be checked by the increased field and the speed will tend to fall until the phase of the pilot generator with respect to the oscillator has shifted sufficiently so that the regulating field current is reduced to an equilibrium value, after which the motor continues to run at constant speed in accordance with the frequency of the oscillator.

Operating tests on the circuit show that the motor will hold in step over line voltage ranges from 100 to 125 volts and will be self-synchronizing over somewhat narrower voltage limits. Thus, under normal conditions all that is necessary from an operating standpoint is to close the switch and wait for the motor to pull into step.

Control Oscillator

The control oscillator is a standard type of vacuum tube oscillator having a frequency precision of the order of 1 part in 1000, when delivering the negligible output of 0.005 watt to the grid circuit of the detector tubes. This frequency is delivered directly to the motor circuits at one end of the line and is transmitted over a separate cable pair to the control circuits at the other end of the line. It was found that the detector tubes would operate successfully over a considerable variation in power level, provided the minimum oscillator output was sufficient.

An interesting alternative method was developed in which the synchronizing channel between stations may be omitted entirely, but this method was not used in the present system as the additional cost was not justified. The method, however, is described as it may prove of value if television transmission over long distances is considered.

Mr. W. A. Marrison in his paper "A High Precision Standard of Frequency," *Proceedings I. R. E.*, July, 1929, described a crystal controlled oscillator which would maintain a precision as to frequency of 1 part in 10,000,000. This oscillator employs a quartz crystal as its primary means of control and by means of secondary circuits, the natural period of the crystal, which is approximately 100,000 cycles, may be stepped down to lower frequencies which are more convenient for such purposes as motor control.

By this means, a frequency of the desired value may be obtained with a precision so great that the speed of the scanning disks under control of the above described circuit will be so nearly perfect that no synchronization channel at all is required. For example, if the period of observation of the television image is 5 minutes, the scanning disk will make 5300 revolutions when operating at a speed of 1060 rev. per min. Assuming a precision of control of 1 part in 10,000,000, the maximum error during the 5 minute interval will be 5300 divided by 10,000,000 or about 1/2000 of 1 revolution. Expressed in degrees on the periphery of the disk, this is equivalent to approximately 1/6 of 1 degree or since the width of the television image with 72 holes in the scanning disk is 5 degrees, the image will drift 1/30 of a frame width during the 5 minute interval If the speed of the scanning disk at the other end drifts an equal amount in the opposite direction, the displacement of the television image will be only 1/15 of a frame width, which is a tolerable amount of drift.

From a practical standpoint, however, it is apparent that the additional cost of very precise independent oscillators would be greater than the cost of providing the synchronization channel, except possibly for transmission over long distances.

Framing

Referring to Fig. 16, it will be noted that a phase shifter is provided between the oscillator and the input terminals to the control circuit. This phase shifter is designed with a split phase primary member producing a rotating magnetic field. The secondary member is single phase and is mounted on a shaft provided with a handle. By rotating the handle of the phase shifter in the desired direction, the frequency delivered from the phase shifter will be the algebraic sum of the frequencies of the oscillator plus the frequency of rotation of the armature of the phase shifter. It is, therefore, a simple matter for the operator at the receiving end to momentarily increase or decrease the control frequency and thus bring the picture into frame.

Conclusion

During the development of the control system, one of the first difficulties encountered was hunting of the controlled motor. The problem of hunting, of course, becomes more difficult of solution the greater the precision of speed regulation desired and the greater the moment of inertia of the load connected to the motor, the latter statement applying only to controlled systems of the synchronous type. Since the moment of inertia of the scanning disk is large relative to that of the motor armature, it is seen that the conditions for securing stable rotation would be unfavorable in both the above mentioned respects if the scanning disk were mounted directly on the motor shaft. The hydraulically damped type of coupling above described was, therefore, inserted between the motor shaft and the scanning disk. It was found, however, that hunting still occurred. A further analysis of the problem showed that the axis of the field flux of the motor was shifting back and forth across the pole faces. The damping winding shown in Fig. 18 was then added with a marked improvement. It was also observed that a strong series field on the motor assisted in securing stability and it was, in fact, necessary to employ all three expedients to secure satisfactory performance. In the system as finally developed the television image, if disturbed by a momentary load such as the pressure of the hand against the disk, would come back to rest within approximately one second, there being two oscillations during this interval. In actual operation, it was found that the normal fluctuations in line voltage occurring on the commercial power supply produced no transients of sufficient magnitude to cause any objectional instability in the received image.

In conclusion, it should be pointed out that this type of control system could be equally well employed with larger motors for other applications requiring precise speed regulation. While the circuit described

is applicable only to a d-c. motor, a similar system may be applied to an a-c. motor substituting a saturating reactor in place of the regulating field winding in the manner described by the author in his paper[7] presented before the Society of Motion Picture Engineers, September, 1928.

PART III—SOUND TRANSMISSION SYSTEM

By D. G. Blattner[8] Associate, A. I. E. E. and L. G. Bostwick[8] Non-member

From the very beginning the ultimate goal of the communication engineer has been to annihilate distance and establish between remotely located parties the effect of face to face communication. Means for accomplishing this goal must of course involve the reproduction at some particular point of both visual and aural effects originated at another and it goes without saying that the two types of effects must be mutually coordinated if the result is to be of the best.

In the design of a sound transmission system to be correlated with a visual system, the requirements as to perfection of results desired are no more stringent than for other high grade sound reproducing systems[9] that have been described in the literature from time to time. Rather in this case the peculiarities of the system are largely those incidental to the adaptation of old technique to meet new conditions.

The principal limitation of the sound system imposed by the visual system is that the use be relieved of all necessity of holding a telephone in close proximity to the head. Such a limitation is highly desirable in order to secure the most natural pose of the features and the most satisfactory scanning. Obviously, the best way of meeting this limitation is by the use of telephone instruments of the type adapted for picking up and reproducing sounds at a distance. The use of such instruments has the further advantage that they can be located near the vision screen and so reproduce any peculiarities in tone quality that would result if the speaker were actually located at the position of the image. Of course, the sharpness of this perspective effect obtained is influenced by the loudness of both the original and the reproduced sounds but the matter of location of instruments is also very important.

It would thus seem that the use of distant pick-up and distant projecting instruments offers certain rather fundamental advantages but it is also true that it presents certain other disadvantages. One of the disadvantages is that the distant pick-up microphone gives less output than a close-up device because of the reduced sound pressure on the diaphram; also a sound producing device to give suitable reception at a distance must be supplied with a higher transmission level than would a close-up instrument. It thus becomes necessary to provide for obtaining greater gain in transmission and greater electrical power capacity than would be required were the instruments held close to the head. The use of the more elaborate transmission facilities is in itself disadvantageous but it also tends to increase the feed-back from the loud speaker to the microphone, also the effect of any noise at the microphone position or at the listening position tends to interfere more seriously with the successful conduct of conversation. In the design of the two-way television system under discussion it was felt that it would be possible to overcome these technical objections to the distant type instruments and that the advantages mentioned would justify any measures necessary to do so.

The question of instruments was solved by the use of the Western Electric 394 condenser type transmitter[10] and a dynamic direct radiator loud speaker. The transmitter is one of the type generally used for phonograph and sound picture recording and for other purposes where good quality, high stability, and quietness of operation are essential. The direct radiator type of loud speaker was used instead of the usual horn type because of the limited mounting space available. It consists of a dynamic structure with a rigid duralumin diaphram about 3 in. in diameter flexibly supported at the edge and radiating directly into free air. While such a structure is not highly efficient and permits of only a small sound power output these considerations are of secondary importance in this case. The instruments were located in the front wall of the booth about 2 ft. from the position of the user and adjacent to the viewing screen in order to enhance the perspective as described above, the microphone being above and the loud speaker below as shown in Fig. 20. These instruments, in this particular case, were connected into a 4-wire circuit although in certain cases it might be desirable to use a 2-wire circuit. Such a change would of course be entirely feasible. The remainder of the apparatus used consisted of amplifiers located at the transmitting end of each channel and an attenuator at the receiving end, the two ends being connected by means of a loop of approximately 3 miles of non-loaded non-equalized cable. The amplifiers and the attenuators were each readily adjustable so that the sounds of different speakers could be reproduced at the optimum loudness. Observation of the performance of the system was made possible in each of the control rooms by means of a monitoring head type receiver bridged across the mid-point of an attenuator tying the two channels together. The attenuation used in the monitoring circuit was such as to give no audible feed-back in either booth. The results obtained with this step-up were considered satisfactory from the standpoint of

7. S. M. P. E. *Transactions*, Vol. 12, No. 35, p. 696.

8. Telephone Engineers, Bell Telephone Laboratories, New York, N. Y.

9. *Public Address Systems*, by J. P. Maxfield and I. W. Green in A. I. E. E., Feb. 14, 1923; *High Quality Recording and Reproducing of Music and Speech*, by J. P. Maxfield and H. C. Harrison, A. I. E. E., Feb. 1926.

10. E. C. Wente in *Physical Review*, May 1922.

both volume and quality. Ready recognition of familiar voices and the association of the source of the reproduced sounds with the image were the usual occurrence. Fig. 21 shows in block form the complete circuit set-up and Fig. 22 shows the combined response frequency characteristic of the microphone, amplifier, and loud speaker. The ordinates of this curve represent variations in sound pressure from the loud speaker for constant pressure on the transmitter diaphram. These data were obtained with the loud speaker located in a heavily damped room. The measurements were made on the sound axis at a distance of 2 ft., representing the relative position of the observer under conditions of actual use.

In setting up such a system the chief consideration is in regard to the acoustic feed-back from the loud

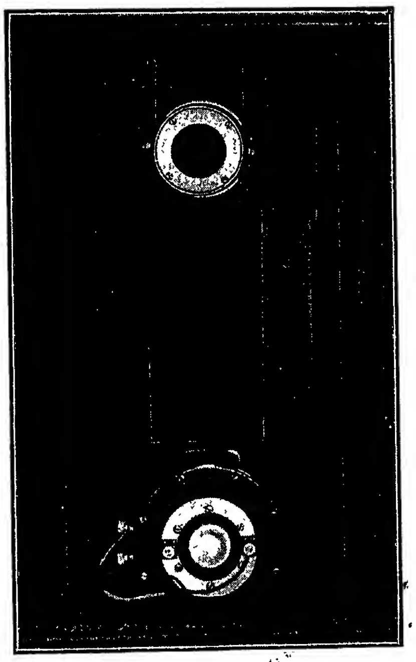


Fig. 20—Microphone and Loud Speaker in Position Above and Below Television Scanning and Viewing Aperture

speaker to the microphone and in this connection the design of the booth is an important factor. The booth must necessarily be so shaped that the user, looking at the viewing screen, can be satisfactorily scanned and the light reflected from the scanned areas will strike the banks of photoelectric cells required for the reproduction of the visual likeness. This requires that the person scanned be located in close proximity to the scanning disk and to the photoelectric cells as well as to the microphone and loud speaker. Such an arrangement is objectionable from an acoustic standpoint because in the present state of development the cells are necessarily large and poor absorbers of sound. They thus tend to cause part of the sound output from the loud speaker to reflect back into the microphone. If the sound so reflected or fed-back is equal or greater in magnitude than the original sound picked up and is of the proper phase relation, the system will "sing" and become of no practical use. A further effect of the design of the booth is that, as a closed cavity, it tends to cause sounds of a certain pitch range to be accentuated. To reduce these effects as far as possible, the television booths were made as large as other considerations would permit and all surfaces were covered where

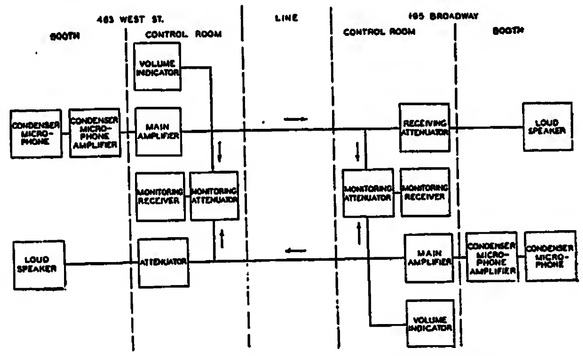


Fig. 21—Circuit Diagram for Sound Transmission System for Two-Way Television

possible with acoustic absorbing material. They have a floor area of about 35 sq. ft. and are about 8 ft. high. Because of the increased transmission required for the proper interpretation of sounds in the presence of noise, the booths were made of heavy masonry material to insulate the user and the microphone from the noise incidental to the rotating parts of the television apparatus. It was thus necessary to project the scanning beam and to view the illuminated image through a

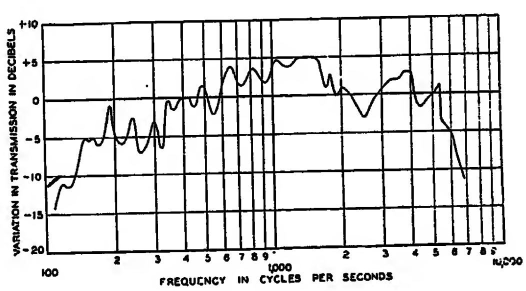


Fig. 22—Response Frequency Characteristic of Microphone, Amplifier and Loud Speaker

window located in the front wall. The microphone and the loud speaker were fitted into this wall, which was then covered over with a thin screen to improve the appearance as shown in Fig. 3. These means effectively reduced the noise in the booth to an unnoticeable amount and reduced reflection effects to the extent that the voice of the average speaker talking in a conversational manner could be reproduced at a loudness best suited

to the general effect. The optimum loudness seemed to be about the same as would be obtained from the speaker direct at a distance of 10 ft., the apparent distance between the image and the observer. At this loudness the gain of the amplifiers was 12 db. less than that required to cause singing.

While the system demonstrated was operated over a distance of only a few miles, it will be appreciated that the same facilities might have been used over much greater distances. Thus for the first time in the history of electrical communication it can be said that complete freedom of exchange of both visual and aural expression between distant users of the telephone has been made possible.

Discussion

N. S. Amstutz: It is with no little thrill that I arise to congratulate the Institute and Dr. Ives on a realization of the vision of one of those dreamers who thirty-six years ago wrote about "Visual Telegraphy" and assumed the role of a prophet, outlining a two-way working system to be used in combination with a telephone circuit.[1] There was described a television sending circuit, a television receiving circuit, a speech transmission circuit and a motor synchronizing circuit. The one-way television circuit and scanning disk device of Nipkow was described in detail, among a number of other proposals. The simultaneous sending and receiving of television currents was by means of two separate cylinders directly connected to a synchronous motor, each cylinder carried a group of openings arranged spirally.

It is indeed a great personal satisfaction to have the dreams of yesteryear come true and this opportunity is taken to congratulate Dr. Ives along with other workers, such as Jenkins at Washington, Alexanderson at Schenectady, and Baird of London, England, all of whom, thanks to sensitive light responsive devices, neon lamps, carrier currents, ultra precision apparatus, adequate financing and technical staffs, are hastening the day when television will not only be spectacular but harnessed to the service of man.

Dr. Ives, in his address referred to television as having been "in the air" for a long time, as far back as the Arabian Nights. Conjecture reverts to an incident described in Dr. Guthries "General History of the World" 1764, Vol. VII pages three and four in which portraits were made and sent in some mysterious manner during the reign of the twenty-sixth califf of the house of Al Abbas, circa A. D. 1037. This is referred to as follows "Avicenna, was obliged to fly to Forjan, where Washmakin reigned. Upon this, Mahmud, having got one of his portraits, ordered a great number of copies of it to be made and dispersed all over the east, that Avicenna might be seized." * * * "Washmakin knew him, by one of his portraits which had been sent him by Sultan Mahmud." The engineers of today may well wonder how the feat described above was accomplished.

1. "Electricity," (New York) Feb. 28, 1894, pp. 77-80, and March 14, 1894, pp. 110-111.

Effects of Lightning Voltages on Rotating Machines and Methods of Protecting Against Them

BY F. D. FIELDER[1] and EDWARD BECK[1]
Associate, A. I. E. E. — Member, A. I. E. E.

Synopsis.—Rotating machines directly connected to overhead lines are subject to damage from lightning surges. Many methods of protection against such damage are possible, several of which are discussed in this paper. Laboratory experiments have been made to show the normal distribution under various steepnesses of waves, and the improvement of unsatisfactory distributions by means of condensers or lightning arresters connected to various parts of the windings has been studied.

THE purpose of this paper is to discuss means of protecting rotating machines directly connected to overhead lines from damage by lightning voltages. In order to select proper methods of protection, it is necessary to determine the distribution of surge voltages in the windings of machines under various cases of applied voltage and with different methods of protection. An investigation of this problem has been made and is described in this paper.

THE PROBLEM

There are two problems involved; one is the limitation of the surge voltages which may be impressed on the insulation between the windings and ground to a value less than its puncture voltage; the other is the limitation of the voltage impressed on the insulation between turns to a safe value. The voltage impressed between windings and ground depends principally upon the magnitude of the transient voltage which reaches the machine through the overhead line; the voltage impressed between turns of the winding depends on both the magnitude and wave front of the incoming tra[redacted] and upon the distributed capacity and indu[redacted] the windings. The protection of the ma[redacted] these voltages can be accomplished by [redacted] the magnitudes of the incoming su[redacted] by properly applied lightning ar[redacted]nts of the incoming surges can [redacted]erminals of the machine by the i[redacted]ed inductance or capacity, or bo[redacted]it ahead of the machine; or the v[redacted]ion in the machine can be altered by t[redacted] of external apparatus at various points [redacted]ng. These methods will be discussed at [redacted] later in the paper.

[redacted]ENT PRACTISE

On th[redacted]as been true in the past that no spe[redacted]e been taken to protect rotating ma[redacted]y connected to overhead lines. It is, ho[redacted]lly recognized that it is more difficult to p[redacted]hine of this kind against damage by surge v[redacted]n a transformer, since, for structural reasons, t[redacted]ion used in generators or motors is not as resistant to impulse voltages. In rotating machinery, the space for insulation in slots is limited; it is impracticable to pad end turns; and as yet the use of oil as an insulating medium is quite limited. For these reasons it is usually recommended that motors or generators be connected to overhead lines through the medium of an insulating transformer. In many cases, however, it is desirable to eliminate the transformer for economic reasons, and then, with the machine connected to an overhead line, the problem of protection becomes of considerable importance. The usual lightning arrester protection given to transformers has been inadequate in some cases of machine protection. Because of the unequal distribution of the surge voltage in the windings, if it enters them with a steep front, the trouble has usually consisted in breakdown of insulation between turns or coils rather than from windings to ground. A lightning arrester limits the magnitude of the surge voltage to ground, thereby preventing insulation failures to ground, but it exerts little if any effect on the steepness of the wave-front. The voltages which will exist across the insulation between turns is determined by the crest voltage of the applied surge, by the length of time it takes to reach this crest value, and by the distributed capacity and inductance of the windings. Hence it is possible that although the magnitude of the incoming surge is limited by an arrester to a value sufficiently small to prevent damage to the insulation to ground, the wave-front of the surge may be steep enough to cause such a voltage distribution in the machine windings that the insulation between certain turns may be overstressed and damaged. Since the magnitude of these voltages between turns is also dependent upon the magnitude of the surge voltage permitted to enter the machine, a reduction in this entering surge voltage will reduce the stresses on the windings. It has been recommended, therefore, that in applying arresters to machines directly connected to overhead lines, arresters of the lowest possible rating be applied in order that the surge voltages shall be limited to the greatest possible degree. In applying arresters to transformers, it is usually the practise to apply arresters of ratings sufficiently high to withstand possible system overvoltages or unbalance of voltage to ground. Where transformers are concerned such protection is adequate, but in the case of rotating machines

[redacted] of the Westinghouse Elec. & Mfg. Co., East [redacted] Pa.

[redacted] at the Summer Convention of the A. I. E. E., Toronto, June 23-27, 1930.

the margin of safety against damage by lightning is often not sufficient. Therefore, it has been recommended in many cases that when arresters are applied to such machines, they be chosen to withstand only the probable, and not the possible, maximum circuit voltages, and that the risk of an occasional arrester failure be run and accepted rather than the risk of damage to a machine. So, for instance, arresters designed for solidly grounded neutral circuits have for the sake of the added protection against lightning thus secured, been applied to machines feeding, or fed from, ungrounded or poorly grounded systems, but with full recognition of the fact that if the voltages to ground become displaced, (as they readily may except on well grounded systems), an arrester may be damaged and require replacement. This is done on the basis that the cost of replacing a lightning arrester is small compared to the economic loss involved in a damaged machine. On the whole, this practise has shown quite satisfactory results; it still leaves some room for improvement however, in that by the use of auxiliary means, the stresses in the windings can be reduced, and the likelihood of damage to the protective equipment, from circuit voltages exceeding the arrester ratings, avoided.

As pointed out in the foregoing, the danger of damage resides principally in the possibility of large voltage stresses between turns caused by non-uniform distribution in the windings when a surge enters. When the surge voltage first enters the machine, the potentials developed across various parts of the windings are determined by the electrostatic field conditions in the windings; in other words, by the relations of the distributed capacities. As the surge penetrates further into the windings, these conditions change; hence, the voltage conditions also change; and it is not until surge current flows throughout the windings that the inductance of the windings plays a major part in the voltage distribution. The theory of the voltage distribution has been described in various papers.[1, 2]

Experimental Tests

In order to investigate the potentials to which machine windings may be subjected when surges of various shapes enter, a series of tests was made in the High Voltage Laboratory at Trafford City on a commercial rotating machine. These tests were made on a standard 5000-kv-a., 4000-volt, three-phase, 60-cycle, 900-rev. per min., synchronous condenser. The machine had two parallel groups of windings per phase, each group containing eight coils, with five turns per coil. Well insulated taps were brought out from each of the eight coils, as well as from each of the five turns of the first line-side coil. Surges of various wave-fronts were applied to the windings and cathode ray oscillograms were obtained at each tap.

Fig. 1 shows the method by which the surges were applied to the windings. The main condenser bank was charged to a constant voltage, and then tripped by a three-point gap with the same impulse which initiated the cathode beam of the oscillograph. Then, for purposes of oscillograph synchronization, the surge was passed through a 500-foot cable to the terminal of the generator winding. A linear timing system was used, with a single sweep of the cathode beam across the film initiated by a tap near the beginning of the cable. The wave-front of the applied surge was controlled by a small inductance connected between the bank of condensers and the cable. A surge impedance at the generator end prevented cable reflections. Voltages at the various taps of the winding were measured by capacity potentiometers, directly connected to the oscillograph. Two potentiometers made it possible to measure differences between taps wherever desirable.

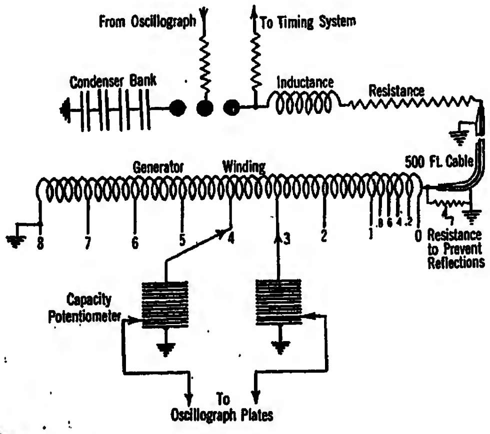


Fig. 1—Test Circuit Diagram

[redacted]he results, two groups of curves are used. [redacted]nsists of a careful replotting of the actual [redacted]m each tap; these curves are merely co[redacted]ams on a percentage basis. The second[redacted]is derived from the first group by consider[redacted]ns at any definite time. For example, where[redacted]t is taken as the crest value of the applied vo[redacted]the first curve shows the per cent voltage to [redacted]each tap. If one particular instant is consid[redacted]t the time corresponding to one microsecond[redacted]urge first reaches the windings,—it will be [redacted]certain distribution obtains at this time. T[redacted]is most readily shown by plotting per[redacted]o ground against coil tap or per cent of the[redacted]e microsecond later, as may be seen by co[redacted]e curves at two microseconds, the distrib[redacted] changed. A family of curves adequately[redacted] the distribution at various times is thus obt[redacted] progressing along the time scale of the first[redacted] curves. Since this method shows the resul[redacted] quickly and more completely, it will be used[redacted] paper for all tests. In considering the result[redacted]

1. For references see Bibliography.

evident that the upper envelope of the curves indicates the maximum voltage to ground; also, the slope of these curves indicates the stress in any coil, the greatest slope showing the worst condition for any particular test. The amount of voltage stress across any coil is determined from the curves showing per cent of voltage,

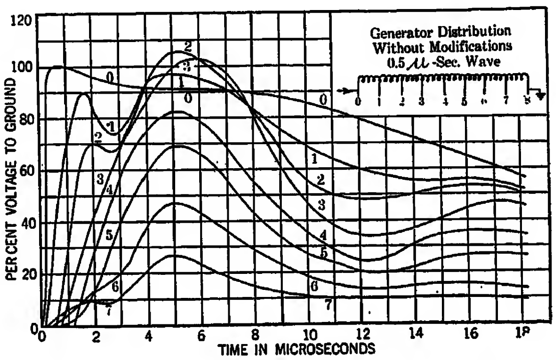


Fig. 2—Voltage—Time Records Obtained on Unmodified Winding, with ½-Microsecond Wave

plotted against coil taps or per cent of winding by considering the voltage difference across the taps of the coil at any instant.

Two waves were used for most of the tests; one was a wave with a rapid rise which increased from zero to crest value in one-half microsecond; the other wave, obtained with a small inductance in the circuit, rose to crest value in approximately two microseconds. In the light of recent data on the shapes of actual lightning surges, it appears that the wave-fronts of the majority of lightning surges which reach apparatus are not so steep as those applied in these tests; hence the tests, (particularly those made with the one-half microsecond wave-front), probably represent more severe conditions than will be experienced in practise. To show further the effect of the change in equivalent frequency a third wave was applied to the unmodified winding. This wave rose to crest value in twelve microseconds. To show comparative results which hold for any applied voltage, curves are plotted on a per cent voltage-to-ground basis. Actually, the wave used had a maximum value of 6300 volts. All waves decreased from crest value to an average of 60 per cent after 20 microseconds with the generator connected.

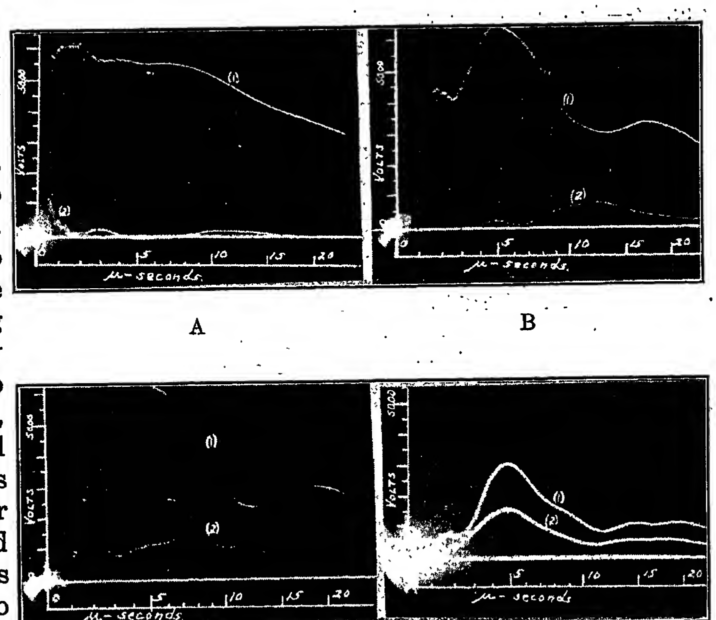
Notation

The generator taps were numbered arbitrarily 0, 1, 2, 3, 4, 5, 6, 7, 8, from line end to ground, 0 being the line side and 8 the actual ground connection. Taps on the first five turns of the first coil were numbered, 0.2, 0.4, 0.6, and 0.8. The oscillograms showed a fairly uniform distribution on these first turns, so they were plotted separately only whenever high stresses were obtained.

Unmodified Distribution

The first problem was to determine the voltage distribution throughout the unmodified winding for the various waves under consideration. Fig. 2 shows the replotted oscillograms for the one-half microsecond wave, and Fig. 3 shows four typical oscillograms. Fig. 4 shows the results again replotted with the winding as abscissa. The worst stress occurs across the first coil shortly after the wave strikes the winding, and amounts to 80 per cent of the applied voltage. This stress is rapidly relieved, for only 0.2 of a microsecond later, this stress has been reduced to 60 per cent. One microsecond after the application of the surge the stress across the first coil becomes 30 per cent. The greatest voltage to ground is obtained after about five microseconds, and amounts to 106 per cent of the impressed voltage. It occurs between the second and third coils from the line end.

The voltage which exists (in these tests) across any particular coil, is determined from either the curves of Fig. 4 or those of Fig. 2, considering the differences in voltage to ground existing at the ends of the coil at any instant. Typical curves of the voltage stresses existing



A B

C D

Fig. 3—Four Typical Oscillograms, Obtained on Unmodified Winding, with ½-Microsecond Wave

A. 1. Applied voltage wave (0-8)
2. Voltage difference across first turn (0-.2)
B. 1. Voltage from tap 2 to ground (2-8)
2. Voltage difference across third coil (2-3)
C. 1. Voltage from tap 3 to ground (3-8)
2. Voltage difference across fourth coil (3-4)
D. 1. Voltage from tap 6 to ground (6-8)
2. Voltage difference across seventh coil (6-7)

across coils are shown in Fig. 5 for Coils 1 and 4, plotted in terms of per cent of kv. applied to the total winding against time measured from the instant the applied surge strikes the line end (Tap 0) of the winding. Similar curves may be plotted for any coil under this test condition or those recorded in Figs. 6, 9, 10, 11, 12, or 13.

These curves may be translated into actual potentials. For example, consider a 22,000-volt machine with solidly grounded neutral; the normal working voltage per phase is then 12,700, and with eight coils, the voltage per coil would be 1600. Now suppose an arrester installed at the machine terminals to ground, which would limit the magnitude of the applied lightning

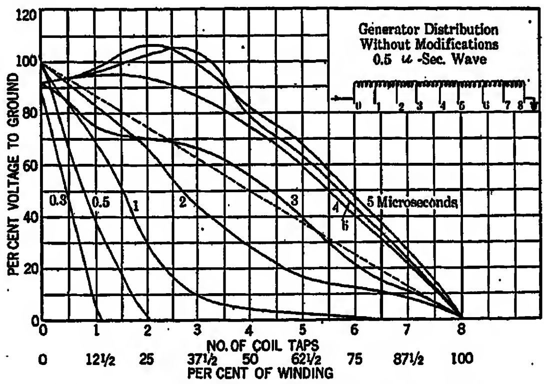


FIG. 4—REPLOT OF FIG. 2, UNMODIFIED WINDING WITH ½-MICROSECOND WAVE

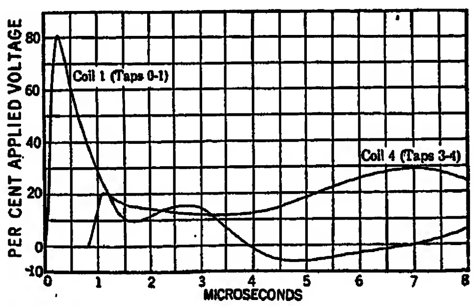


FIG. 5—TYPICAL VOLTAGE STRESSES ACROSS COILS FOR CASE SHOWN IN FIGS. 2 AND 4

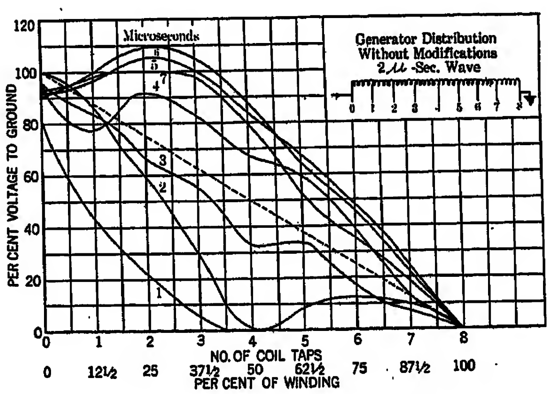


FIG. 6—REPLOT OF OSCILLOGRAMS, UNMODIFIED WINDING WITH 2-MICROSECOND WAVE

voltage to 3.5 times the normal working voltage,—a ratio which generally obtains with the commercially available arresters of this class,—or a surge voltage corresponding to an equivalent 60 cycle r. m. s. value of about 44,000 volts. If the applied surge rises to this value in 0.5 microseconds, Fig. 5 shows that the maximum voltage stress across coil No. 1 will be 80 per cent of 44,000 or 34,000 volts r. m. s.; in other words $\frac{34,000}{1600}$ or 21 times normal, whereas with uniform

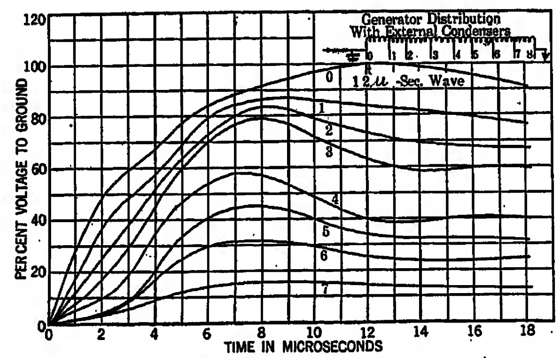


FIG. 7—VOLTAGE—TIME RECORDS OBTAINED ON UNMODIFIED WINDING WITH 12-MICROSECOND WAVE

distribution in the windings the stress on the coils would be 12.5 per cent of 44,000 or 5500 volts, or 3.5 times normal for an exceedingly short period of time. As announced before the Institute last October and Jan-

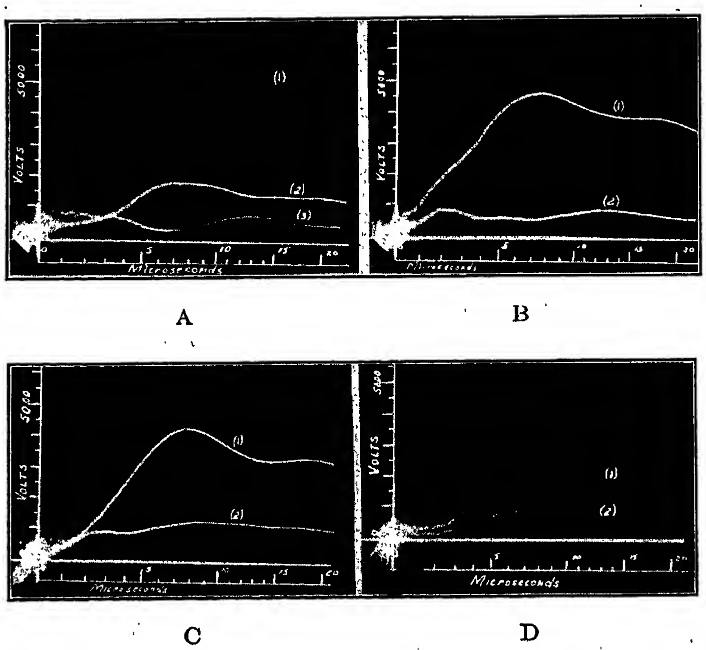


FIG. 8—FOUR TYPICAL OSCILLOGRAMS, OBTAINED ON UNMODIFIED WINDING, WITH 12-MICROSECOND WAVE

A. 1. Applied voltage wave (0-8)
 2. Voltage from tap 6 to ground (6-8)
 3. Voltage difference across first coil (0-1)
B. 1. Voltage from tap 2 to ground (2-8)
 2. Voltage difference across third coil (2-3)
C. 1. Voltage from tap 3 to ground (3-8)
 2. Voltage difference across fourth coil (3-4)
D. 1. Voltage from tap 5 to ground (5-8)
 2. Voltage difference across sixth coil (6-7)

uary lightning arrester developments now in progress indicate that these voltages may in the future be further reduced in the ratio of approximately 2.5/3.5.

The results obtained with the two-microsecond wave show a less severe initial distribution, Fig. 6. The

greatest stress again occurs on the first coil, but this time it is only 40 per cent of the applied wave. Nearly as great are the stresses obtained later: 30 per cent over coil 3 after two microseconds, and 25 per cent over the last coil, 8, after about five microseconds. The maximum voltage to ground due to internal resonance is 108 per cent of the applied voltage at six microseconds.

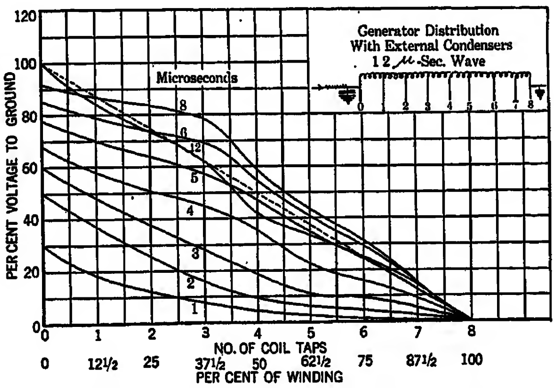


Fig. 9—Replot of Fig. 7 Unmodified Winding with 12-Microsecond Wave

The effect of a considerably slower wave rising to crest value in 12 microseconds was studied. The curves, like the theory, indicate that the distribution would be more uniform with slower waves; so this was checked. The modification in this case was obtained by inserting a condenser at the generator end of the cable in much the same way as the front can be modified in practise. Fig. 7 shows the oscillograms replotted, Fig. 8, four typical oscillograms, and Fig. 9, the distribution curves for the winding. It will be seen that the stresses are

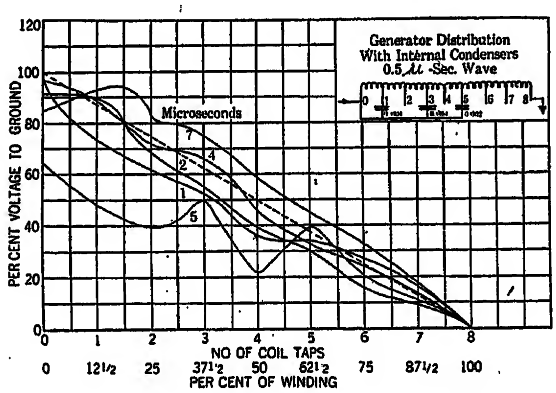


Fig. 10—Replot of Oscillograms, Winding Equipped with Internal Condensers, with ½-Microsecond Wave

comparatively small, in no case exceeding a maximum of 20 per cent across any individual coil.

The point to which the modification of the wave must be carried for a satisfactory distribution depends upon the natural frequency of the generator, for if the impressed wave has an equivalent frequency less than the natural frequency of the machine, little distortion of the distribution is possible.

Distribution Modified by Distributed Capacitors

In accordance with theory it follows that the addition of small capacities connected to points in the winding would improve the voltage distribution obtained with steep fronts. Accordingly several condensers varying from 0.001 to 0.005 μ f. capacity were connected from the line to the coils. Instead of taking oscillograms of each of the many possible combinations, the effects of each combination were observed on the oscillograph screen. At first, condensers were connected to each

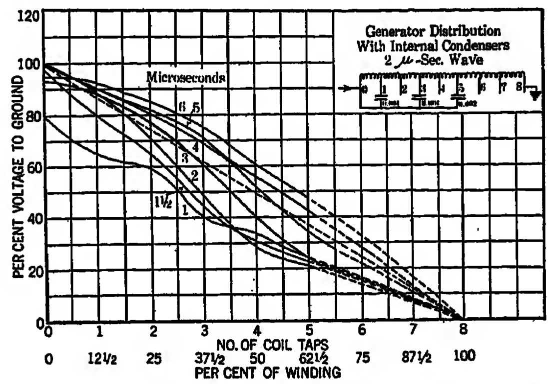


Fig. 11—Replot of Oscillograms, Winding Equipped with Internal Condensers, with 2-Microsecond Wave

tap, but it was later found that practically as good correction was obtained with fewer condensers; this, of course, means fewer taps in a machine actually protected in this manner. The final arrangement employed three condensers: one of 0.004-μ f. capacity,

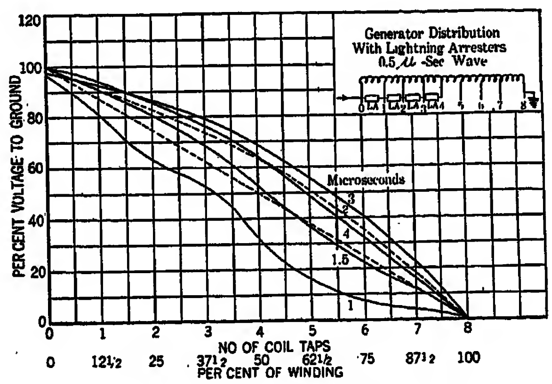


Fig. 12—Replot of Oscillograms, Winding Equipped with Internal Lightning Arresters, with ½-Microsecond Wave

connected between the high side and the first coil (Tap 1); one of 0.004-μ f. capacity connected between the high-voltage side and the third coil (Tap 3); and one of 0.002-μ f. capacity connected between the high-voltage side and the fifth coil (Tap 5).

Fig. 10 shows the results obtained with the ½-microsecond wave and these condensers. The curves show that with a maximum stress of less than 25 per cent on any coil at any time and voltage to ground always less than the applied surge; high-voltage concentrations have been eliminated. In comparison with the original

curve, this curve suggests another way of explaining the improvement; that is, the auxiliary condensers pass the surge to the lower coils before it could pass through the winding itself, thus relieving the concentration over the first coils. Fig. 11, obtained with the two-microsecond wave, approaches a perfect distribution, and shows far better characteristics than were obtained with the unmodified winding. For this wave, the maximum

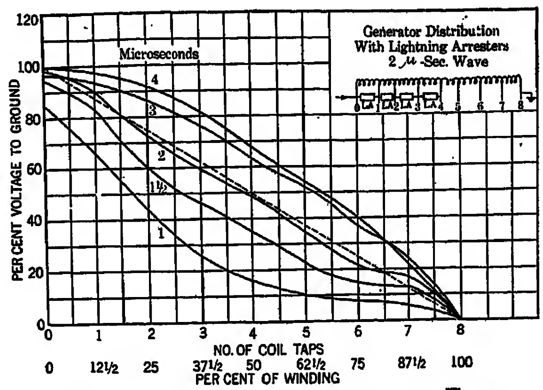


FIG. 13—REPLOT OF OSCILLOGRAMS, WINDING EQUIPPED WITH INTERNAL LIGHTNING ARRESTERS, WITH 2-MICROSECOND WAVE

stresses compared with a value of 12.5 per cent which would result from perfect distribution are only slightly greater than 15 per cent for all coils.

PROTECTION AGAINST UNEVEN DISTRIBUTION BY MEANS OF SHUNT LIGHTNING ARRESTER UNITS

In this case, small arrester units were placed across the coils having the greater stresses, thus limiting the voltage to less than a dangerous value. As the voltage across the first coil reaches the breakdown value of the arrester, the arrester will operate, absorb a portion of the energy of the wave, and pass the remainder on to the second coil. An arrester across the second coil will operate in the same way, and so on until the surge is completely distributed. In this test arrester units with a rating of about 600 volts each were used, and a good distribution was obtained with this protection across the first four coils. The applied surge was of such magnitude that after passing through the first four coils and arresters, it was no longer harmful. Fig. 12 shows the resulting distribution with the ½-microsecond wave representing considerable improvement over the original distribution. The greatest stresses were only slightly above 20 per cent. With the two-microsecond wave, (Fig. 13), similar results were obtained. On the whole, the results obtained with the lightning arresters were as good as those obtained with the internal condensers, and show stresses and voltage to ground of approximately the same values.

The tests described in the foregoing show that the voltage distribution in the machine windings can be made practically uniform by several methods.

I. CHANGING THE SHAPE OF THE APPLIED WAVE

If the wave-front of the applied surge has a sufficiently gradual rise, the distribution will be quite uniform as shown in Figs. 7 and 9. As shown by these figures the wave-front of the incoming surge can be sloped off by the insertion of capacity between the machine terminals and earth. This capacity, together with the surge impedance of the line, provides a circuit in which it will take a definite time to charge the condenser up to the full voltage of the incoming surge through the surge impedance of the line, provided the surge originated at some distance from the machine. The time necessary to charge the condenser is dependent upon the values of surge impedance and capacity The circuit is similar to that of a resistance and condenser in series, with voltage suddenly applied. If the capacity at the machine terminals is made large enough, the wave-front can be sloped off to any desired degree. However, unless the capacity is extremely large, this imposes no limit on the magnitude of the surge impressed, which, in turn, means that the windings may still be stressed above their ability; hence, a voltage limiting device in the form of a lightning arrester or gap must also be introduced. The rate of voltage rise up to the beginning of the discharge of the arrester is then determined by the magnitude of the applied surge, the capacity placed at the machine terminals, and the surge impedance of the line, if the surge originated at a distance. In the case of high-voltage surges of steep front, the time in which the voltage reaches the limit imposed on it by the arrester,—that is the wave front preceding arrester discharge,—may be very short. Hence, although the voltage impressed on the machine is limited, the time to reach its crest may be short, and uneven distribution result. To preserve uniform distribution and low magnitude, it is desirable that the time in which the voltage applied to the machine rises to its maximum (the terminal voltage of the lightning arrester used) be long enough to give uniform distribution in the windings. This is accomplished by resorting to the use of a choke coil in conjunction with the capacity and the arrester. The

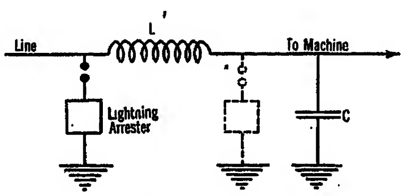


FIG. 14—PROTECTIVE EQUIPMENT TO LIMIT THE MAGNITUDE AND STEEPNESS OF SURGE VOLTAGE APPLIED TO MACHINE

circuit is as shown in Fig. 14. The use of such an inductance has a further advantage in that the sloping off effect of the condenser is then active, even for surges originating near the machine. The incoming surge first strikes the arrester which limits its magnitude to a definite value. The lightning arrester voltage then passes through the choke coil to charge the condenser. Thus, regardless of the magnitude of the incoming surge the voltage available for charging the condenser is

always substantially the same. The time necessary to charge the condenser up to its maximum potential is determined by the period of the circuit consisting of the inductance of the choke coil and the capacity of the condenser. The theory of this will not be discussed here; it can be found in various papers and text books.[3,4,5] Briefly stated, an approximation of the actual (sufficiently accurate for our purposes) is that the period of this circuit is $2\pi\sqrt{LC}$ and the time required to reach the maximum charge is one-half of the period, or roughly $3\sqrt{LC}$. The voltage to which the condenser may theoretically be charged is $2e$, where e is the applied surge voltage,—in this case the voltage permitted by the lightning arrester. Certain investigations made by means of surge generators and cathode ray oscillographs indicate that in the type of circuit shown in Fig. 14, the condenser voltage may overshoot 50 per cent; that is, may reach $1.5e$. This can be reduced by shunting the choke coil by a suitable resistor; or can be prevented by the application of a second lightning arrester at the condenser. By this combination of devices, then, the magnitude and wave-front of the voltage applied to the machine can be fixed for the steepest possible lightning surge by selecting the magnitudes of L and C to give the desired wave front. The desired effect can be approached by the use of an arrester and capacity without the choke coil; but here the rate of rise of voltage preceding the arrester discharge is governed by the magnitude of the incoming lightning surge, and will therefore vary. Unless the capacity is very large this may cause non-uniform distribution. Consequently the use of an inductance in combination with the capacity is preferred.

In the application of the equipment described in the foregoing, the amount of inductance that may be used in the choke coil is usually limited by the reactance that may be placed in series with the machine. Often the current limiting reactor, if one is employed, can be used as the choke coil, except in some cases when its insulation and turn spacing may require special attention. In such cases, the required capacity is at once determined. For instance, suppose it is desired to protect a 60-cycle generator whose characteristics are such that an applied surge which rises to its crest in not less than ten microseconds will give a safe distribution, and that with this is to be used a current limiting reactor of one ohm in each phase; the inductance of this reactor is then 2.65 millihenrys. The capacity required to slope an abrupt incoming surge off to a 10-microsecond front is then 0.0042 μ f. With such a combination of arresters, choke coil, and capacity, the magnitude of the surge applied to the machine windings will be limited to the terminal voltage of the arresters which is below the danger value for the insulation of the machine windings to ground. To this it will rise in approximately 10 microseconds, thereby providing a uniform distribution and safe magnitude of voltage.

II. The Use of Cable Between the Machine and the Overhead Line

It is well known that when an overhead line terminates in a cable, surges traveling in the overhead line when they penetrate the cable undergo considerable change because of the relation of the surge impedances of the cable and the overhead line. The surge that enters the cable is much reduced, (for the usual cases to about 20 per cent of the magnitude it had in the line), and its front is correspondingly sloped off. If the cable is long, attenuation further slopes off the front of the surge and reduces its crest; a long cable will therefore exert considerable beneficial effect. In short cables, however, successive reflections of the surge gradually raises its voltage in steps until it exceeds the magnitude of the original surge in the line.[3,4] It is questionable whether cables of the length usually employed have sufficient protective effect to safeguard the machine in the case of severe lightning transients; particularly since lines of the relatively low voltages usually involved are generally overinsulated, or supported on wood poles, so that their flashover voltages are high and therefore the magnitude of the surges which can produce voltage in the cable is also great.

III. Condensers Tapped to Points of the Winding

As was to be expected from theory, the tests showed that the voltage distribution in the windings can be made sufficiently uniform to be safe by shunting portions of the windings by employing small capacities. These capacities may be either external to the machine or built in it. They may be of relatively low voltage rating, and the leads to them may be small, although they must be insulated for the working voltage which exists at the point where they are tapped to the windings. Where shunt capacities are used, a lightning arrester should be applied to the terminals of the machine to limit the magnitude of the lightning voltages applied to the windings.

There are theoretical possibilities in the design of stator windings with shielding so introduced that the voltage will be distributed uniformly. Whether or not these are economically practical remains to be seen.

IV. Lightning Arresters in Shunt with Portions of the Winding

In a manner similar to Section III, the distribution may be made uniform by shunting portions of the winding by lightning arresters whose voltage rating corresponds to the working voltage which will exist across their terminals. These arresters prevent the building up of dangerous voltages across the windings with which they are in shunt. The arresters may be either external to the machine, or built in it; and again, the leads to them may be small, but must be insulated for the working voltage which exists at the point where they are tapped to the windings. The tests indicate that

relatively few arresters in shunt with a few sections of the winding at the line end will alter the distribution sufficiently; however, if lightning arresters are placed in shunt with parts of the winding throughout its entire length, the arrester usually applied to the machine terminals may be dispensed with.

In the above discussion it has been assumed that the neutral of the machine is grounded. If the neutral is free or grounded through resistance, the above data on distribution will, in general, still hold. Where the neutral is free or grounded through a high resistance, it is to be recommended that a lightning arrester be applied from the neutral point to ground; otherwise high voltages to ground may appear at the neutral because of reflections.

There are thus several methods by which a rotating machine connected to overhead circuits may be protected against lightning:

1. Interposing an insulating transformer protected by lightning arresters between the machine and the overhead line. (This is common practise today, particularly in those locations where lightning conditions are severe.)

2. Combinations of inductance, capacity, and arresters connected in the machine circuits. (This provides effective protection at a moderate cost, and in the authors' opinion is to be preferred to the use of capacity without inductance. In considering the construction of a certain large 22,000-volt synchronous condenser for direct connection to an overhead line, the cost of such protective equipment was estimated at approximately 15 per cent of the cost of the machine. This includes the cost of a reactor, which if already required for current limiting purposes, should be compensated for in the cost of the protective equipment.)

3. Shunting parts of the winding by capacities with arresters applied to the machine terminals. (This method is equally effective. It may require some modification of machine design in order to bring out the leads to the condensers.)

4. Shunting parts of the winding by lightning arresters. (This is another effective method resembling Method 3. It has the advantage of possibly permitting the elimination of the arresters now usual at the machine terminals, but also may require modification of the machine design.)

5. Application of arresters to the machine terminals only. (This has no effect on the voltage distribution in the windings, and the arresters, if so applied, should have the lowest possible rating. It may be considered an expedient; the previously described methods are to be preferred from the standpoint of protection.)

6. Interposing a length of cable between the machine and the overhead line. (Short lengths of cable will exert little beneficial effect, long ones may. Other methods are preferable.)

7. Machines with specially shielded windings, with arresters applied to the machine terminals. (This requires more or less sweeping changes in design which at the present writing do not appear economically practical.)

The present tendency in machine design is to avoid the necessity of tapping the windings which would require that additional leads be brought over or through end turns and to avoid installing in the end winding space supplementary devices not inherently necessary to the proper operation of the machine. For this reason it is thought preferable to introduce protective measures entirely external to the machine, by the method described in I.

In the application of any of the above methods except 1, each case should receive special consideration, as the characteristics of the protective equipment must be fitted to the characteristics of the machine involved.

Appendix

The purpose of this Appendix is to present in graphical form, so far as possible, the behavior of a lightning transient when it strikes a machine or the protective equipment installed at the machine terminals. It is

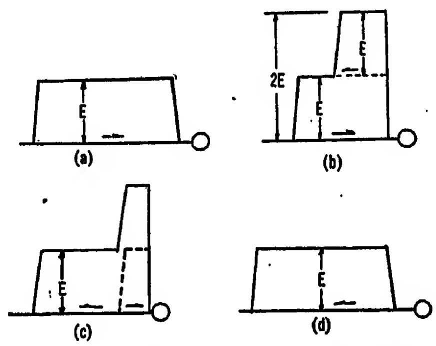


FIG. 15—SURGE VOLTAGE WHICH WILL APPEAR AT MACHINE TERMINALS IF IT IS UNPROTECTED

(a) Incoming traveling wave of voltage E
(b) and (c) Approximately 2 E appears to ground at the machine for for the duration of the surge
(d) The reflected wave passes back into the system

not intended that this shall be a rigid analysis calculated on the basis of the actual shape of lightning transients as they have been measured, nor on the actual shape of the voltage waves that appear across lightning arrester terminals. This would involve complications unnecessary for our purpose, which is to present in as simple a manner as possible the behavior of the voltages at the protective equipment. Consequently it is assumed that the lightning transient impressed on the apparatus is of a simple shape, practically rectangular; that is, with an abrupt front, a flat top, and an abrupt tail. It is also assumed that the lightning arrester terminal voltage is of this same shape. Actually these conditions do not exist, but for the sake of simplicity, they are assumed. The fundamental picture which the authors wish to present is most easily drawn and visualized by this means. Actual cases may be analyzed step by step in a similar manner. Much of the material presented is not new; it can be found in text books. But it was

thought to be of some value to present that which is pertinent to the subject of the paper.

With this apology, let us consider the case of Fig. 15,—a traveling wave approaching an unprotected machine. It is well known from theory and experiment that when surge voltages reach an open end or the high surge impedance of a winding they will virtually double.

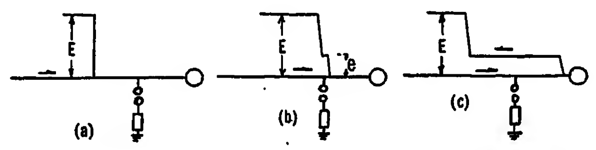


FIG. 16—SURGE VOLTAGE WHICH WILL APPEAR AT MACHINE TERMINALS IF IT IS PROTECTED BY A LIGHTNING ARRESTER

(a) Incoming traveling wave of voltage E
(b) Arrester limits the transient voltage to e
(d) The voltage which reaches the machine is e

Hence, if the machine is unprotected, the voltage applied to the machine windings is practically $2E$, the voltage distribution in the windings will be determined by the time it takes the voltage to increase from zero to $2E$, and the magnitudes of these distributed voltages are determined by $2E$.

If the machine is protected by a lightning arrester, the conditions are as in Fig. 16. If the distance between the arrester and the machine is great, the voltage at the machine may reach twice the arrester voltage; that is, $2e$, by reflection in a manner similar to that

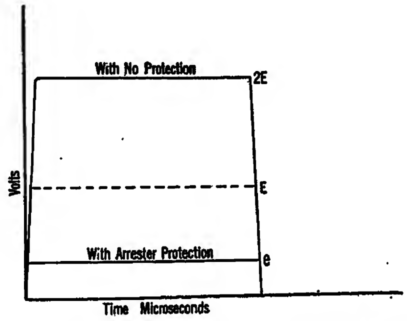


FIG. 17—VOLTAGES WHICH WILL APPEAR AT THE MACHINE TERMINALS IF UNPROTECTED AND IF PROTECTED BY A LIGHTNING ARRESTER

shown in Fig. 17. This will, however, be modified if there are present busses, taps, and other lines. If the arrester is installed close to the machine, the voltage impressed on the machine is e, the distribution in the windings is determined by the time it takes the voltage to rise from zero to e, and the magnitude of these distributed voltages is determined by the value of e.

Let us now consider the application of a condenser alone at the machine terminals, as in Fig. 18. With a traveling wave approaching the condenser through the surge impedance of the line, the condenser will slope off the wave-front. If there were no protective equipment at all, the incoming wave would double by reflection to $2E$, as in Fig. 15; hence the voltage applied to the condenser through the surge impedance is $2E$, to which voltage the condenser will ultimately charge if the surge is of sufficient duration. Considering for the moment the equivalent circuit, the condenser voltage at any time t microseconds after the voltage is applied is

$$e_c = 2E\,(1-\epsilon^{-t/T}) \qquad (1)$$

$T = RC = ZC =$ the "time constant" of the circuit. Z is assumed 500 ohms, C is the capacity in microfarads, and t and T are expressed in microseconds.

Fig. 19 shows the charging of the condenser. In

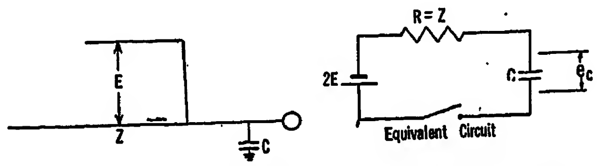


FIG. 18—MACHINE PROTECTED BY A CONDENSER ONLY, AND EQUIVALENT CIRCUIT

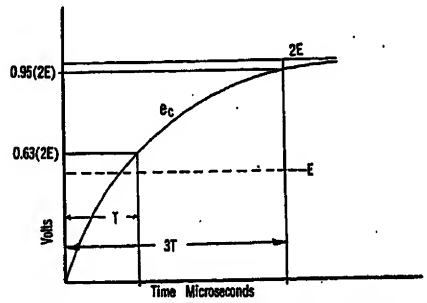


FIG. 19—CURVE SHOWING THE CHARGING OF THE CONDENSER

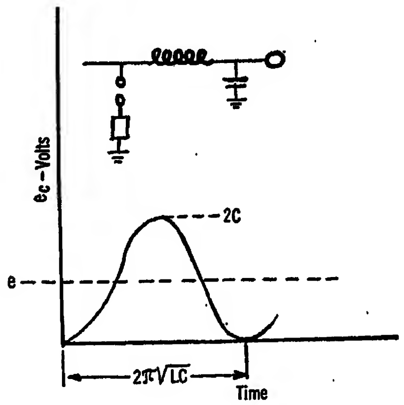


FIG. 20—VOLTAGE AT MACHINE TERMINALS FOR CIRCUIT INDICATED IN FIGURE, ASSUMING NO DAMPING

T microseconds, e_c will equal 0.63 ($2E$) and in $3T$ microseconds e_c equals 0.95 ($2E$); hence to all practical purposes it may be said that e_c will become equal to $2E$ in $3T$ microseconds.

The condenser will slope off the wave, but will not reduce its crest below E unless C is so large that the condenser will be charged to less than E when the duration of the surge is passed. To achieve a reduction in voltage comparable to that of a lightning arrester if a long and high surge occurs, the value of C must be great.

The distribution in the windings, if e_c reached $2\,E$, is determined by $3\,T$, and the magnitude of these distributed voltages is determined by the maximum e_c, in this case $2\,E$. Thus, although the voltage distribution may be good, the magnitudes of the voltages impressed may be higher than the insulation can withstand.

It would be desirable to limit the magnitude of the voltage impressed on the machine, and to fix the time constant of the protective circuit used so that $3\,T$ will be large enough to assure a uniform distribution. The voltage can be limited by an arrester, but if an arrester is used, together with a condenser of only moderate capacity, the rate of voltage rise at the terminals of the arrester and machine will be determined by the capacity of the condenser and the magnitude of the incoming surge; that is, until the condenser has charged to a voltage sufficiently high to discharge the arrester, the voltage applied to the machine windings will increase along the curve of Fig. 19, *i. e.*, according to Equation (1), the applied voltage during this period preceding arrester discharge being $2\,E$. When e_c has risen to the arrester discharge voltage, the arrester will limit the magnitude of the voltage impressed on the machine to e; but the time in which the surge voltages rise from O to e may be very short, since we are on the rapidly rising part of the curve of Fig. 19. Thus, although the voltage has been limited by the arrester, the time to reach the crest may have been very brief; and although the surge crest has been limited, the voltage distribution in the windings may be bad. For this reason it is desirable that matters be arranged so that the voltage is first limited to e by the arrester, and that it will be this voltage e which charges the condenser at such a rate that $3\,T$ is sufficiently long to give uniform distribution.

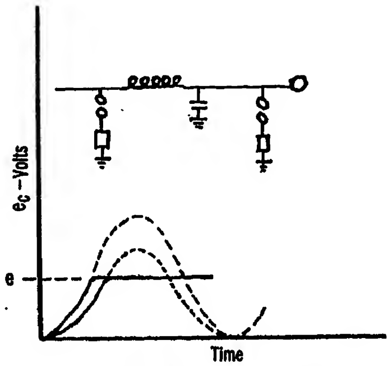


Fig. 21—Voltage at Machine Terminals for Circuit Similar to that of Fig. 20, but Employing an Additional Arrester across the Condenser Terminals; Assuming Both No Damping and Sufficient Damping to Hold e_c to 1.5 e.

This is accomplished by interposing an impedance,—preferably an inductance of considerable value,—between the arrester and the condenser, as in Fig. 14, so that e and not $2\,E$ will charge the condenser through this impedance. The circuit containing this inductance and capacity is an oscillating one with damping depending upon the surge impedance of the line and the impedance of the arrester connected to the line. Let us suppose it is undamped and that no auxiliary arrester is connected across the condenser terminals; the condenser voltage will then oscillate about the voltage e, as in Fig. 20, possibly reaching a value to ground of $2\,e$. Its period will be $2\,\pi\,\sqrt{L\,C}$, and the time required to reach $2\,e$ will be half of this, or roughly $3\,\sqrt{L\,C}$. By this device, then, the magnitude and front of the surge can be controlled. In practise, the condenser voltage is not likely to overshoot to $2\,e$; generally there exists sufficient damping to prevent rises to more than 1.5 e, as indicated by certain controlled surge tests. Increases above e can be entirely prevented by the use of an additional arrester across the condenser terminals as in Fig. 21.

Bibliography

1. J. K. Hodnette, *Effect of Surges on Transformer Windings*, A. I. E. E. Journal, November 1929, p. 829.

2. K. K. Palueff, *The Influence of Transient Voltages on Transformer Design*, A. I. E. E. Quarterly Trans., Vol. 48, July 1929, p. 681.

3. R. Rudenberg, Elektrische Schaltvorgange.

4. Bradfield & John, Telephone and Power Transmission.

5. A. M. Opsahl, "Lightning Surges Measured," *Electrical World*, March 16, 1929.

6. C. M. Laffoon, *Increased Voltages for Synchronous Machines*, A. I. E. E. Quarterly Trans., Jan. 1930, p. 213.

7. J. J. Torok and F. D. Fielder, "High-Voltage Surge Oscillography," *Electric Journal*, July 1929.

Discussion

For discussion of this paper see page 1607.

Voltage Oscillations in Armature Windings Under Lightning Impulses—I

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Associate, A. I. E. E.

Synopsis.—Experience has shown that rotating machinery connected directly to overhead lines is more vulnerable to surges than many other types of apparatus. This fact together with a desire on the part of some to connect important units to the line in this manner, has necessitated a study of the protection problem. Such a study is here described, showing oscillograms taken when steep voltage surges were applied to machine windings, measuring internal voltages to ground which are 200 per cent of the voltage allowed by the terminal lightning arrester. A simple traveling wave analysis of these oscillations is developed, which has successfully explained the peculiarities of over 400 oscillograms taken under various terminal conditions. Practical methods of eliminating the oscillations with neutral impedance are outlined in the light of the theory developed, and oscillographic evidence supporting their reliability is given. A generalized theory of neutral protection is proposed. The importance of wave-front, surge impedance of incoming line, arrester resistance, and other factors is discussed. Methods for protection of the turn insulation and the insulation to ground of such machines are suggested, showing that the lightning arrester only limits the potential of waves entering the machine and cannot control oscillations which may take place within the machine. The advantages of thyrite as a neutral resistor are pointed out in connection with the short-circuit protection, telephone interference, and lighting protection problems of such machines. In Appendix A the test circuits and methods used in the laboratory are discussed in relation to actual field conditions.

Introduction

THE peculiar response of synchronous machinery to transient surges has been realized for some time as a cause of frequent failures of machines connected directly to overhead lines.

One of the fundamental reasons why these transient surges cause so much trouble in electrical apparatus is because they require a definite time to travel a given distance. On an open line a surge travels at the velocity of light, which accounts for the fact that while one point on the line may be at normal line potential at a given instant, another point only a short distance away may be at 100,000 volts at the same instant. In machine windings where these physical circuits of length are concentrated in a frame of iron, the two points in question may be electrically some distance apart while physically there may be only an inch or less insulation between them. Furthermore, these surges obey definite laws of reflection at any discontinuity of circuit giving rise to additional stresses in many cases.

There are several principles which may be followed in reducing these abnormal potentials. One is shielding. Another is to introduce a change in the circuit actuated by the surge itself, having the effect of counterbalancing these abnormal potentials. Another method is that of eliminating the discontinuities of circuit so as to avoid increased stresses due to reflection. In many cases the use of one or more of these forms of protection is possible and necessary for the safety of the insulation of machine windings. This fact is the basis of the paper.

In order to understand how to protect rotating machinery from transient surges it is essential to know how machine windings respond to surges. An investigation with this objective has been made and will be outlined here.

Object

The object of this paper is threefold:

(1) To explain the internal oscillations in machine windings when subjected to steep wave fronts. It is shown by a cathode ray oscillograph study, followed by theoretical considerations, that the highly oscillatory internal voltages rising in some instances to 200 per cent of the terminal voltage, are primarily due to successive reflections of a traveling wave in the machine winding.

(2) To show that the oscillations may be eliminated by connecting between the neutral of the machine and ground, a resistance equal to the characteristic surge impedance of the machine winding.

(3) To present an analysis of the protection of the insulation between turns of machine windings and to ground. It is shown that the voltage stress between turns may be reduced by shielding or by placing a capacitor in parallel with an arrester unit.

Oscillograph Investigation

A cathode ray oscillograph investigation forms the foundation of the study and resulting theory presented in this paper. Three machines were tested ranging from a small 2200-volt induction motor to a 24,000-volt synchronous condenser and all were found to perform in a similar manner under artificial lightning surges. The lightning generator used for the tests was designed to represent electrically an equivalent transmission line of definite surge impedance delivering a given wave. It is felt that this phase of the study is of considerable importance and a detailed analysis and discussion is given in Appendix A, where it is proved that the test circuit used is an accurate representation of transmission line traveling wave conditions.

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

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Oscillogram Characteristics

All of the oscillograms shown in the paper are oscillograms of voltage to ground with respect to time. Each oscillogram is titled with a figure, the key to which is as follows:

A single phase of a machine winding is represented by the rectangle shown in each diagram. In all cases the traveling wave approaches from the left. The point at which the voltage is measured is indicated by an arrow on the winding with the corresponding percentage from line terminal indicated below the arrow. The condition of the opposite end of the winding is important and is given in the usual notation. Hence, Fig. 1 is an oscillographic record of what takes place in the winding of a 24,000-volt machine when a steep wave is applied to its line terminal and the opposite end grounded. The equivalent surge impedance of the lightning generator was very small for these tests. The voltage in all cases is scaled in per cent of the wave which enters the machine winding, this being defined as the applied wave. It will be seen later that this is equivalent to the arrester voltage. The abscissa is time, the reference point in each case being taken at the moment the wave reaches the line terminal of the machine. Similarly, Fig. 2 is the record when the neutral of the same winding is open, the same wave being applied as in Fig. 1. In these tests the rotor was removed and only a single phase of the machine was tested.

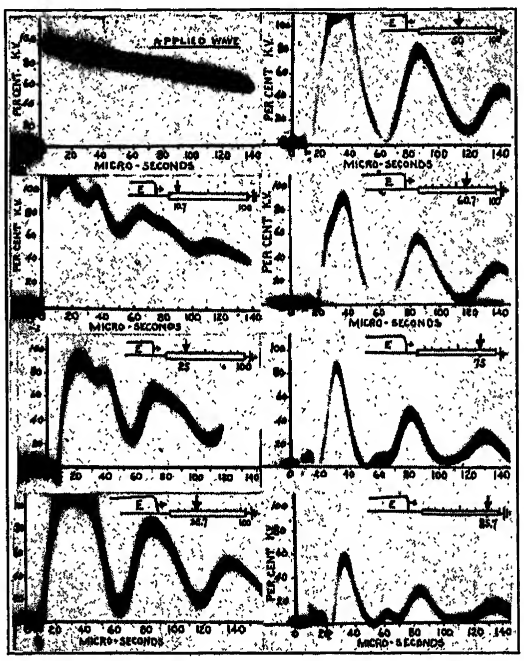

Fig. 1—Oscillations in the Winding of a 24,000-Volt Machine with the Neutral Grounded

A study of these oscillograms will be made here by listing some of the outstanding relations which are apparent.

(1) The maximum voltage with the neutral open is twice that of the neutral grounded.

(2) The frequency of the oscillations with the neutral grounded is twice that of the neutral open.

(3) The time delay of any appreciable voltage rise increases in proportion to the distance from the line terminal at which the voltage is measured.

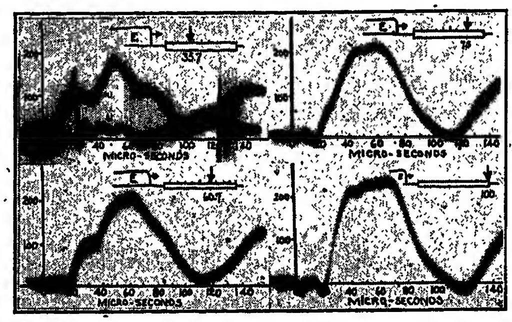

Fig. 2—Oscillations in the Winding of a 24,000-Volt Machine with the Neutral Open

(4) This time delay is the same with the neutral open or grounded.

(5) The voltages oscillations measured at various points in the winding with either the neutral open or grounded are substantially "in phase."

(6) A certain flat top characteristic is evident in many of the oscillograms, it being predominant near the neutral of the open neutral winding and near the line terminal of the grounded neutral winding.

(7) All records are distinctly unidirectional.

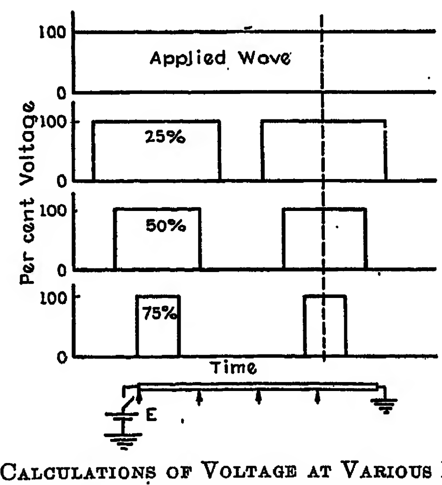

Fig. 3—Calculations of Voltage at Various Points of a Finite Line with the Neutral Grounded

Explanation of Oscillograms

It will be shown that the voltage oscillations bear a marked similarity to those which would occur on a short length of transmission line, when subjected to a similar transient force. Consider the simple case of a suddenly applied voltage to the short line shown at the bottom of Fig. 3. First, when the far end is grounded.

At time $t = 0$ the switch is closed and a voltage

wave, E, will travel out on the line at a velocity depending upon the inductance and capacity of the line per unit length in the well known relation

$$v = \frac{1}{\sqrt{LC}} \quad (1)$$

When the voltage wave reaches the grounded terminal it will reflect with change of sign and return as a negative wave to the source at the same velocity. On

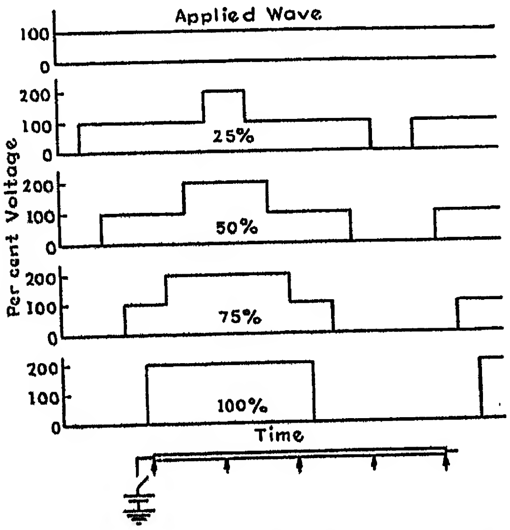

FIG. 4—CALCULATION OF VOLTAGE AT VARIOUS POINTS OF A FINITE LINE WITH THE NEUTRAL OPEN

reaching the source it will again find a grounded condition and reflect with a change of sign and repeat the operation indefinitely. Assuming no attenuation or distortion of the wave, and realizing that the potential at any point on the line is the algebraic sum of the resulting waves, it is easily seen that the voltages to ground which would be recorded by an oscillograph placed along the line would be as shown in Fig. 3.

Now consider the case where the far end of the line is open. When the voltage wave reaches the open neutral it reflects without change of sign and returns on the line, everywhere doubling the voltage to ground. On reaching the source it reflects with change of sign and returns negatively to the open end, reflecting again without change of sign and returning to the source to complete the cycle of its oscillation. Note that this time the wave had to travel twice as far to complete one cycle. Fig. 4 shows what the oscillograph would measure at various points along the line in the above example.

Making a study of Figs. 3 and 4 it is found that each of the seven characteristics which were tabulated in the study of the oscillograms of Figs. 1 and 2 is distinctly true in this case of a simple finite transmission line. These seven characteristics may be considered as criterions of traveling wave phenomena.

This analysis forms a basis for the theory that each phase of a generator winding functions as a finite transmission line to traveling surges arriving at its terminals. It will be noted by inspection that the distortionless calculations of Figs. 3 and 4 form the envelope of the corresponding voltages of Figs. 1 and 2, the latter showing the effect of such factors as losses and series capacity in distorting the wave. The transmission line constants of the generator winding will be discussed later.

As previously pointed out the oscillograms were taken on a single phase. Generally lightning surges involve all three phases. The phase voltages may be divided into two groups, a group which represents the average voltage to ground of all three phases and a group which represents the inequalities in voltage to ground as between the different wires. The first component is really a zero phase component and is practically unaffected by the presence of the rotor. The other group will in general be affected by the presence of the rotor.

The test results given in the paper and the resulting conclusions apply primarily to the first group, although even in this group we may expect small differences in results between the single-phase tests with the rotor

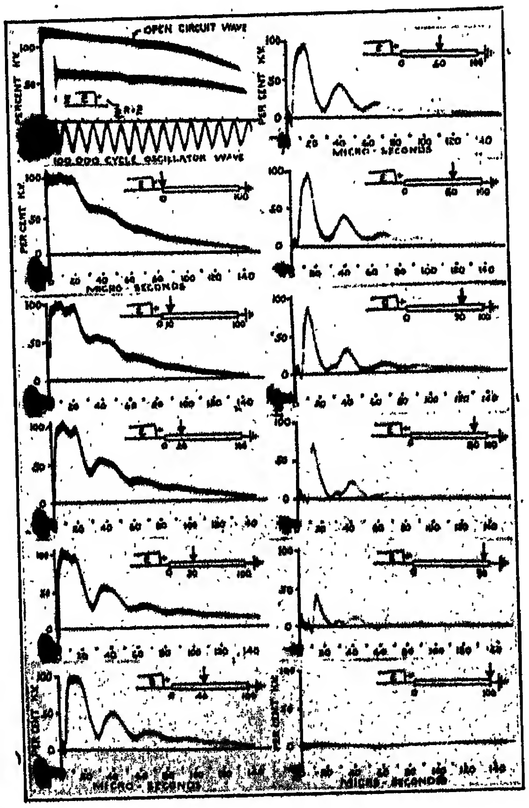

FIG. 5—TESTS ON 6600-VOLT WINDING, NEUTRAL GROUNDED

removed and the first group mentioned above especially in machines of two-thirds pitch. A number of tests with all three phases connected showed that these differences were small in the machines tested.

OSCILLOGRAPHIC DATA

A 6600-volt steel mill motor was then tested, the object being:

(1) To verify the proposed traveling wave theory for machine oscillations.

(2) To obtain additional constants of the transmission line properties of the new windings to be tested.

(3) To test certain methods of eliminating the oscillations which presented themselves in the light of the theory proposed.

The lightning generator for these tests was designed to represent a transmission line of 250 ohms surge impedance delivering a very steep wave. (See Appendix A.) The criterion for such a line is that when a resistance equal to 250 ohms is placed across the open end, the terminal voltage will be half of the open circuit wave. Such a relation is shown in the upper left hand corner of Fig. 5.

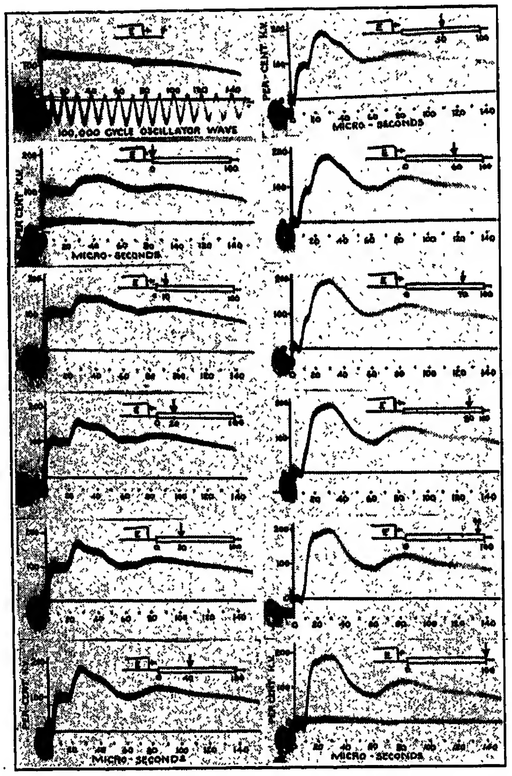

FIG. 6—TESTS ON 6600-VOLT WINDING, NEUTRAL OPEN

When such a circuit is used it not only furnishes the proper voltage wave but also the proper current wave, hence satisfying all the energy relations of a transmission line traveling wave.

The voltage at the winding terminal resulting from such a traveling wave is the drop across the resistance Z_g, (see Appendix A) of the circuit shown in Fig. 7, that is

$$E_g = 2\,E\left(\frac{Z_g}{Z_1 + Z_g}\right) \qquad (2)$$

where $2\,E$ is the open circuit wave, Z_1 = 250 ohms = the surge impedance of the incoming line, and Z_g = 800 ohms = surge impedance of the machine winding as measured by the oscillograph. E_g in the above equation is considered as 100 per cent and all voltages are referred to this as a base. It is the wave which actually enters the winding.

In order to give all oscillograms a definite reference point for which to consider $t = 0$, a special circuit arrangement was resorted to which recorded this

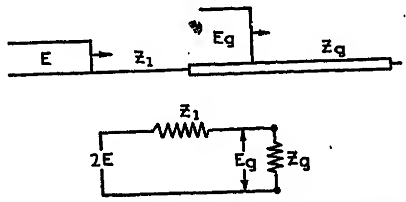

FIG. 7—EQUIVALENT CIRCUIT OF TRANSMISSION LINE MEETING A GENERATOR WINDING

reference point on the oscillograms automatically. Such an arrangement leaves little doubt that the wave requires a definite time to reach a given point in the winding. The true ground potential is shown in the lower right-hand oscillogram of Fig. 5.

Figs. 5 and 6 give the picture story of what takes place in the winding of a 6600-volt machine with the neutral grounded and open. The same relations are evident which were listed in connection with the study of Figs. 1 and 2. The use of the equivalent transmission line of 250 ohms accounts for the minor peculiarities

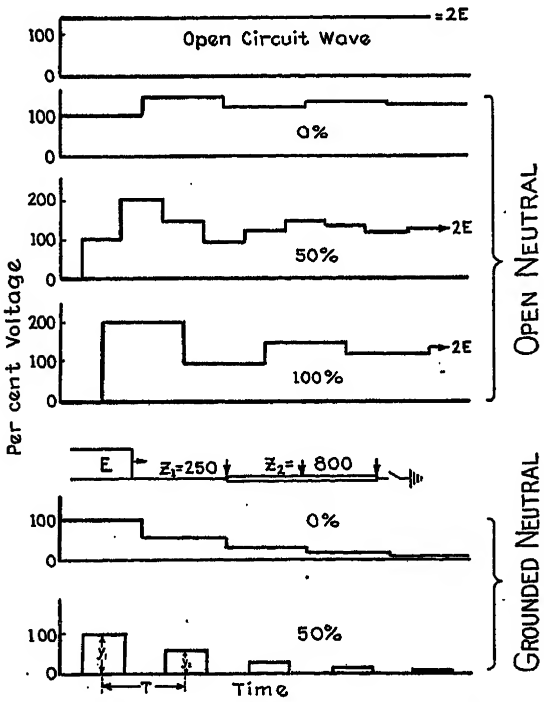

FIG. 8—CALCULATED VOLTAGES IN 6600-VOLT WINDING

of these oscillograms as shown by comparing with the calculated voltages for a few points in the winding as shown in Fig. 8. There is excellent agreement with the recorded voltages. Consider, for instance, the voltage measured at the line terminal when the far end is open. It shows distinctly that the wave returned to the line

terminal on the 800-ohm winding and found a surge impedance of 250 ohms. The resulting voltage at the line terminal would be:

$$E_0 \left\{ \frac{3\,(250) + 800}{250 + 800} \right\} = 1.476\, E_0 \qquad (3)$$

where E_0 is the wave which entered the winding.

This means that part of the wave was again reflected in the winding negatively while part, namely 0.476 per cent, was transmitted to the incoming line, not to return. This loss of part of the wave to the line each time the wave returns to the line terminal accounts for much of the apparent damping of the oscillations. This is best shown in Fig. 8, these voltages being calcu-

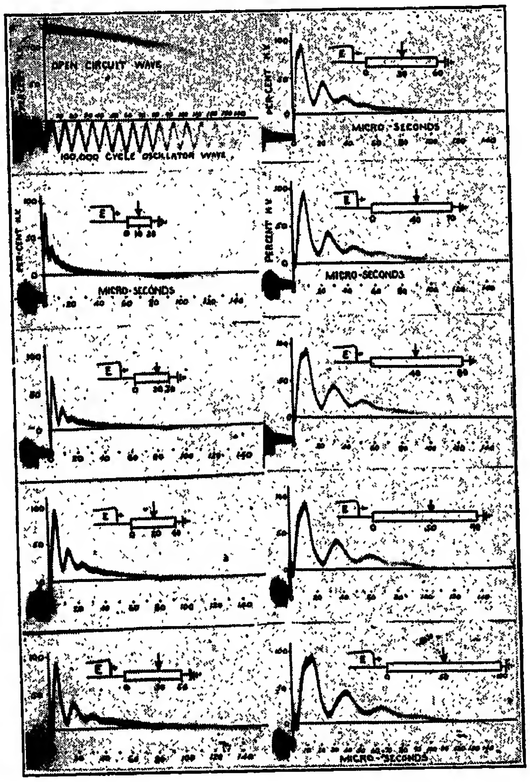

Fig. 9—Test on Fractional Lengths of 6600-Volt Winding—Neutral Grounded

lated on the basis of no loss or distortion in the generator winding. The exact expression for this damping due to the junction loss is shown as Equation (39).

By studying the development of the voltage oscillations on a finite transmission line as shown in Figs. 3, 4, and 8 it will be seen that the period of oscillation in all cases was a direct function of the length of the line, the velocity of wave being fixed. Hence it follows that if a winding behaves as a transmission line, by testing fractional lengths of the winding there should result a linear relation between the period of oscillation and the length of winding tested. Such tests were made on the 6600-volt machine and the oscillograph record is shown in Fig. 9 for the grounded neutral and Fig. 10 for the open neutral. In Fig. 11 the relations between the period of oscillation and length of winding tested, as plotted from Figs. 9 and 10, are shown to be practically linear as the theory indicates. This constitutes an additional proof that such oscillations are due to a reflection phenomenon.

Another test which forms a proof of the proposed theory and also lays the foundation of a practical method of eliminating the oscillations, is based upon the transmission line principle that if a resistance equal to

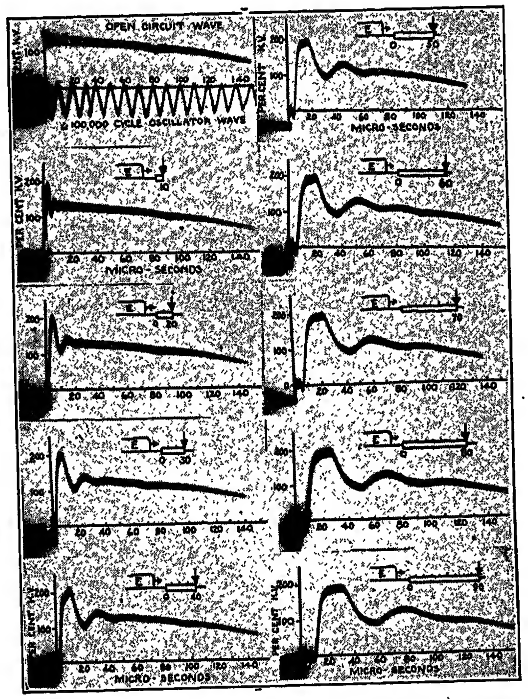

Fig. 10—Test on Fractional Lengths of 6600-Volt Winding—Neutral Open

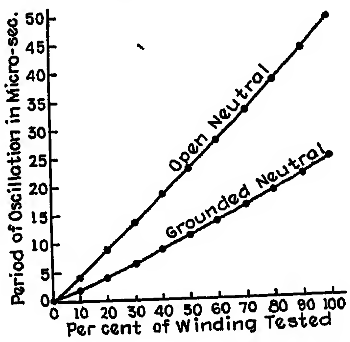

Fig. 11—Relation between Period of Oscillations and Length of Winding Tested

the surge impedance of a line be placed at the end of the line to ground, that any wave arriving at this end will be completely absorbed and there will be no reflection to produce an apparent oscillation on the line.

This follows directly from the simple method developed in Appendix A which states that the condition for which the voltage across the terminal resistance is equal to the traveling wave E, Fig. 7, is that $R = Z_0 = Z_1$. Such a resistance, in effect, indefinitely extends the line.

The surge impedance of the 6600-volt winding was approximately 800 ohms. A resistance of this value was placed in the neutral of a single winding to ground and the same steep wave which previously gave rise to oscillations with the neutral open and grounded was applied. The oscillographic record is shown in Fig. 12.

The result is in accord with the theory. The effect is that of measuring a passing wave at various points along a line from a fixed time reference point. The wave merely passes by, not to return.

Voltage Distribution Curves

From the oscillograms of voltage in the 6600-volt winding taken with the neutral grounded, (Fig. 5) the

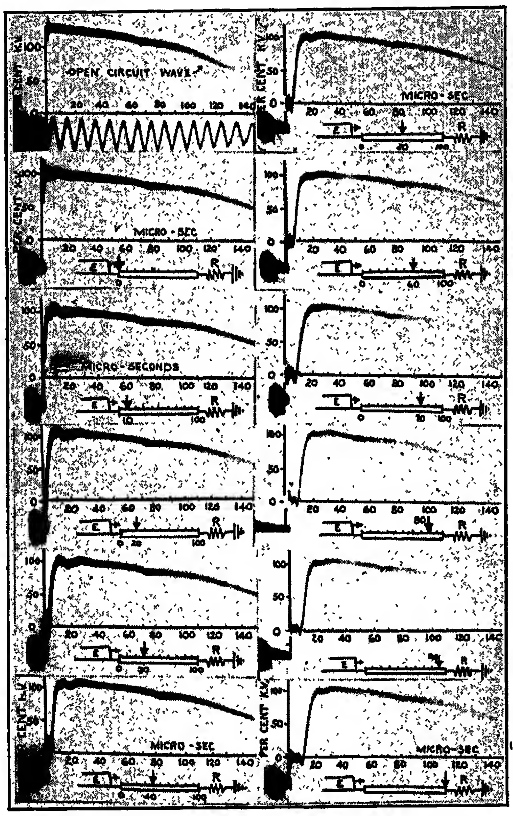

Fig. 12—Tests on 6600-Volt Winding with a Resistance Equal to the Surge Impedance in the Neutral to Ground

voltage distribution curves of Fig. 13 were determined. These curves show the voltages throughout the winding at various times. A careful study of these distribution curves will show that the initial voltage distribution is very low because of the fact that the wave requires a definite time to reach any point in the winding. As time goes on the wave enters the winding; thus the voltage distribution at 5 microseconds shows the position of the wave in the winding at that time. This also shows the distortion of the wave at the end of that time. In 12.5 microseconds the wave reaches the far end of the winding ready to reflect negatively reducing the voltage in the winding at any later time. In short, this traveling of the wave back and forth in the machine winding, reflecting with change of sign at each terminal results in the apparent oscillation of the voltage distribution curves as a standing wave, finally coming to rest at a final distribution depending upon the type of applied wave. If the applied wave is a rectangular wave, infinite in length, the final voltage distribution will be the straight line from 100 per cent voltage at the line terminal to ground potential at the neutral and about which the apparent standing wave oscillation is taking place.

This simple analysis gives a physical interpretation to well known mathematical transformations of any standing wave phenomenon to a traveling wave phenomenon and vice versa. The traveling wave explanation of the oscillation of the voltage distribution curves about the final distribution thus accounts for the change from the initial distribution to the final distribution, this difference being the criterion of a transient condition in the winding.

Rope Analogy

The family of distribution curves shown in Fig. 13 usually suggests the oscillation of a rope or chain of finite length firmly fastened at the far end, with a sudden force applied at the home end raising it a given height (potential) above an initial horizontal position. The oscillations of such a rope are usually considered as a standing wave phenomenon, but from the above analogy it is seen that it may also be explained as a reflection phenomenon of a traveling wave. This suggests that if the reflection can be eliminated the oscillations will be reduced to a minimum.

This can be accomplished by extending the length of the rope indefinitely, so that any traveling wave which results from the suddenly applied force merely travels out on the rope indefinitely.

This may be accomplished in a winding by placing at the end of the winding an impedance to ground equal to the characteristic impedance of the winding, which for a generator is a pure resistance equal to the surge impedance of the winding. Such a resistance has the property of extending the winding to infinity so that any wave traveling in the winding will continue, and have no point of reflection to set up a disturbing oscillation in the machine. The oscillographic demonstration is shown in Fig. 12.

A similar explanation of the oscillations of an open winding can be made by assuming the far end of the finite rope to be free. This is analogous to the voltage rise at the far end of the machine winding to double the applied voltage. Those familiar with the oscillations in open and closed organ pipes will recognize a similar phenomenon.

Generalized Theory of Neutral Protection

The elimination of the oscillations in generator windings by means of a resistance equal to the surge impe-

dance of the winding is a particular example of a general theorem which may be stated as follows:

Any type of apparatus whose internal oscillations under transient conditions can be attributed to reflections of a traveling wave from the terminals of the machine, can be protected from these oscillations by inserting at the neutral terminal to ground an impedance equal to the characteristic impedance of the machine winding.

Such an impedance when tested alone by a given transient force will perform in the same way as the winding to be protected will perform under the same transient force, when the said impedance is in the neutral of the winding to ground. This forms a laboratory verification of the proper impedance to be used in any particular case. Theoretically, if the winding to be considered can be shown to consist of a series impedance Z_1 per unit length and a shunt impedance to ground Z_2 per unit length, the characteristic impedance[12] is $\sqrt{Z_1 Z_2}$. For a transmission line $Z_1 = L\,p$ and $Z_2 = \dfrac{1}{C\,p}$ and the characteristic impedance becomes $\sqrt{\dfrac{L}{C}}$ which is dimensionally ohmic in value. This is readily shown from the fundamental energy relations on a line where

$$\frac{W}{2} = \frac{1}{2} L\,I^2 = \frac{1}{2} C\,E^2 \tag{4}$$

from which,

$$\frac{E}{I} = \sqrt{\frac{L}{C}} \tag{5}$$

the ratio between the voltage and current of a traveling wave and defined as the surge impedance of the line.

Frequency of Oscillations

Consider a winding with a grounded neutral in which the voltage wave reflects with change of sign at each terminal. Where the length of the winding is D miles it is easily seen that the wave, traveling at a velocity v miles per second, will travel $2\,D$ to complete one period of its oscillation, hence

$$2\,D = v\,T \tag{6}$$

where T is the period in seconds of its travel. Now the velocity of the wave is known to be

$$v = \frac{1}{\sqrt{L'\,C'}} \tag{7}$$

where L^1 and C^1 are the constants per mile of winding.

From these simple relations the frequency of oscillation shown on the oscillograms of Figs. 1 and 5 becomes

$$\frac{1}{T} = f = \frac{1}{2\,D\sqrt{L'\,C'}} \tag{8}$$

which reduces to

$$f = \frac{1}{2\,\pi\sqrt{L\,C}} \tag{9}$$

when

$$L = \frac{L'\,D}{\pi} \text{ and } C = \frac{C'\,D}{\pi} \tag{10}$$

These relations are interesting and suggest lumped circuit equivalents of a finite transmission line under transient conditions in that $L'\,D$ and $C'\,D$ are the total inductance and capacity of the winding.

In a similar manner it is obvious that the wave travels four times the length of an open winding to return to its initial starting point resulting in a frequency relation

$$f = \frac{1}{4\,\pi\sqrt{L\,C}} \tag{11}$$

which is just half of the frequency of the previous case.

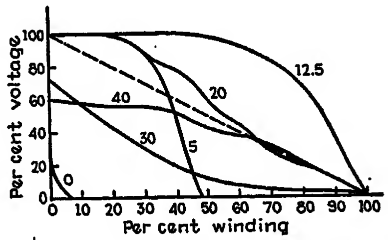

Fig. 13—Distribution Curves of Voltage in Winding of 6600-Volt Machine, Neutral Grounded

Phase Relations

Referring to Figs. 1 and 2 it may be seen that the voltages measured throughout the winding are in time phase as far as the oscillations are concerned. This might suggest that all points in the winding reach their maximum voltage at the same time due to some mutual coupling throughout the winding; however this need not be the case. By studying the development of the calculated voltages as a result of a traveling wave phenomenon, Figs. 3 and 4, it is seen that this phase relation is fully satisfied. It will be observed, however, that the shape of the voltage oscillations are different throughout the winding. This difference is best shown in Fig. 14 where the voltages measured at 33 per cent and 66 per cent in the winding from the line terminal of the 24,000 volt machine are shown for the condition of the neutral grounded. The voltage between these two points is the difference between the two voltages to ground and is seen to be a second harmonic of the fundamental oscillation. The magnitude of this harmonic voltage is a function of the distance between the two points, the velocity of the wave in the winding and the rate of rise of voltage at the respective points. It is inherently caused by the fact that the voltage wave reaches the two points in the winding at different times, both in its initial trip through the winding and on returning through the winding due to reflections

from the terminals. This phase relation is important since it determines the maximum voltage between turns, one of the fundamental considerations in designing a competent protective unit.

By examining the oscillograms or the calculated curves for the voltages between other parts of the winding it will be found that many interesting harmonic relations exist. The voltage between the line terminal and the midpoint of the winding will be found to be of fundamental frequency. Should the voltage be determined between any two points chosen at random, curves will result which if analyzed would be found to contain many harmonics.

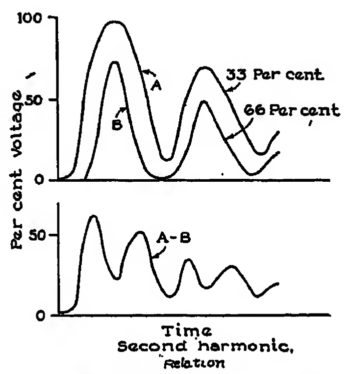

FIG. 14—VOLTAGE BETWEEN 33.3 AND 66.6 PER CENT OF WINDING—NEUTRAL GROUNDED

TRANSMISSION LINE CONSTANTS OF GENERATOR WINDINGS

Any distributed circuit with Z_1 as a series element and Z_2 as a shunt element, has another very characteristic constant, namely the velocity of propagation[12] of a wave along the system proportional to $\sqrt{\frac{Z_2}{Z_1}}$. On a transmission line where the series element is inductance and the shunt element capacitance this constant becomes $v = \frac{1}{\sqrt{L\,C}}$. The surge impedances of standard transmission lines are usually between 300 and 600 ohms and the velocity of propagation of the waves is usually close to the speed of light or 186,000 miles per second.

Since a generator winding has been found to function substantially as a finite line it must also possess similar characteristic constants. These are readily obtained from the oscillograms.

Consider the tests on the 6600-volt winding shown in Figs. 5, 6, 9, 10, and 12. The surge impedance may be determined either from the difference between the open circuit voltage and the terminal voltage (provided the surge impedance of the incoming line is known, which in this case was 250 ohms), or more accurately from the proper value of resistance to prevent reflections at the neutral. Hence the resistance used in Fig. 12 to prevent reflections was 800 ohms and this may be considered to be the surge impedance of the winding.

If we assume that the wave follows the actual metallic path through the winding the velocity of propagation is just as readily obtained from the frequency of oscillations, knowing the actual length of the metallic circuit which for the case of the 6600-volt winding was 0.301 miles. Thus the average velocity of the wave through this winding was found to be 24,000 miles per second.

It would seem reasonable to assume that the velocity of the wave in the slot is much slower than in the end turns of the machine. To determine this point more accurately 10 coils were tested in series in air and the velocity of propagation of the wave found to be 125,000 miles a second. This was considered a little faster than the wave would actually travel in the end turns because the latter would have a higher inductance and capacity due to the proximity of the core of the machine. For this reason the velocity in the end turns was considered as 100,000 miles a second.

Using this velocity in the end turns it was found that the velocity of the wave in the slot portion was very close to 10,500 miles per second. This velocity was obtained within a few per cent on the three machines tested.

In order to establish one equivalent velocity in the winding it becomes necessary to determine the equivalent length of the generator winding by reducing the end turns to equivalent slot dimensions. This is determined from the fact that the wave travels approximately ten times as fast in the end turns as in the slot portion, hence, where D is the core length in inches, $M\,L\,T$ is the mean length of turn in inches, and N is the turns in series per phase, the effective length of the winding becomes

TABLE I
TABULATION OF TRANSMISSION LINE CONSTANTS OF GENERATOR WINDINGS
Windings Reduced to Equivalent Slot Basis

Machine voltage	Equivalent length of winding in miles $N\,l = K\,(1.8\,D + 0.1\,M\,L\,T)\,N$ (see Eq. 12)	Time to traverse winding (microseconds)	Velocity of wave in winding (miles per second)	Surge impedance of winding (ohms)	Inductance per mile of slot (henrys)	Capacitance per mile of slot (microfarads)	Equivalent length of transmission line (miles)
V	$N\,l$	t	v	Z_g	L'	C'	L
2,200	0.0343	3.4	10,100	685	0.0675	0.144	0.627
6,600	0.1325	12.5	10,600	800	0.0755	0.118	2.32
24,000	0.272	25	10,900	1000	0.0918	0.0918	4.65

$$N\,l = (2\,D + 0.1\,(M\,L\,T - 2\,D)\,N$$
$$N\,l = (1.8\,D + 0.1\,M\,L\,T)\,N \quad (12)$$

The surge impedance of the various machines, the machine dimensions, velocity of propagation, capacity, and inductance per unit length as determined from tests are shown in Table I. The slot relations and arrangement of conductors are shown in Fig. 15 for the machines tested.

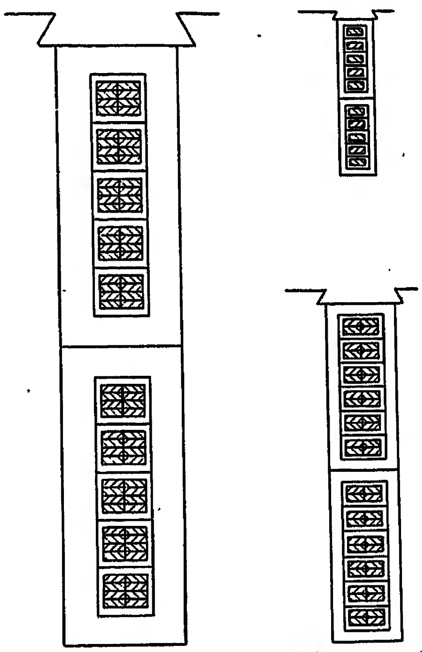

FIG. 15—SLOT PROPORTION OF MACHINES TESTED

It will be noted from the table that the velocity of propagation in each case is slightly slower as the size of the slot is reduced around the conductor. It is also interesting to note that the surge impedance is largest with the larger slot, showing that as the voltage of the machine is increased, necessitating more insulation and a larger slot, the rate of change of capacity is greater than the rate of change in inductance.

It is believed that the surge impedance and propagation constants as found for the machines under consideration are in general the same for the types of machine windings tested, the surge impedance being the more important as it will determine the maximum allowable resistance which can safely be put in an open neutral in case of a transient disturbance.

ELIMINATION OF OSCILLATIONS

It follows from the traveling wave theory that the magnitude of the oscillations can be reduced by slowing up the front of the wave applied to a winding. This fact is appreciated when the analysis of Figs. 3 and 4 is made using a wave with a slower front. This reduction in voltage oscillations with the slower wave is inherently due to the fact that the front of the wave reflects in the winding to reduce the maximum voltages which would have occurred.

Another way of explaining this fact is by the principle of superposition. Any positive wave with a sloping front can be considered to be equivalent to a rectangular positive wave and a negative wave equal to the difference between the rectangular wave and the given wave. Allow both of these waves to reach the machine simultaneously and solve for the internal voltages for each separately. The resulting solutions may then be added in their proper time relations, obtaining the correct result. The smaller negative wave will produce predominantly negative voltages which give rise to the lowering of the resulting stresses. In this way it is readily seen that if the applied wave rises slowly enough, no oscillations would take place; moreover, that the front of the wave applied to an open winding would have to be twice as slow as that applied to the same winding with a grounded neutral to produce the same reduction in oscillations. In this way the natural frequency of a winding under any given conditions is a measure of the wave-front which will reduce these oscillations. A good criterion of such a wave is one which rises to 90 per cent of its maximum value in a time equivalent to the period of the natural frequency of the winding. Such a wave will not eliminate the oscillations, but will reduce them to a reasonable value.

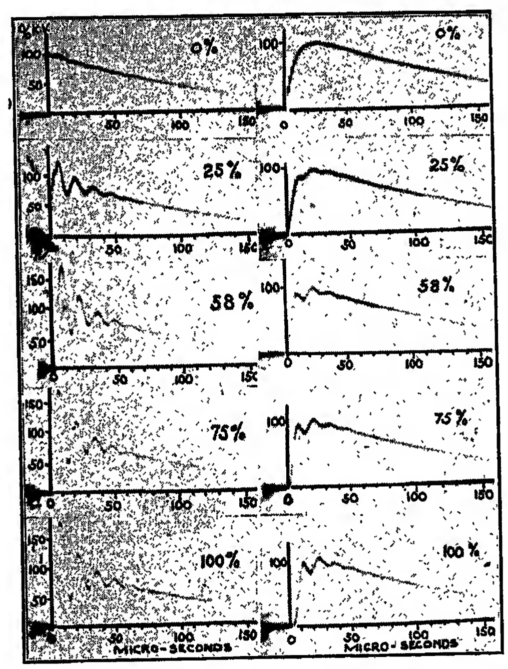

FIG. 16—OSCILLOGRAMS SHOWING THE REDUCTION IN OSCILLATIONS WITH SLOW WAVE FRONTS IN A 2200-VOLT INDUCTION MOTOR

Fig. 16 shows the reduction in internal oscillations in a 2200-volt induction motor winding with the far end of the winding open, when a 13-microsecond wave is applied, in comparison with the corresponding oscillations for a very steep wave. In studying Fig. 16 alone, one might draw the conclusion that the oscillations are necessarily associated with steep waves, but such is not the case. It is true that the oscillations would not

have occurred if the steep front had not been applied, but the oscillations are caused by the reflection phenomena at the terminals of the winding. Fig. 17 shows the oscillations in the same winding with the same steep wave applied but in the right hand case the neutral of the winding was equipped with a resistance to ground equal to 685 ohms, the surge impedance of the winding. Here it is seen that the oscillations have been practically eliminated by preventing reflections in the winding.

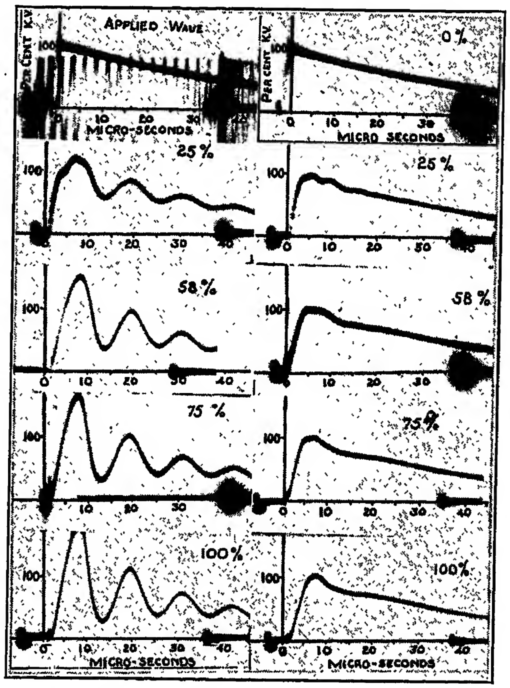

FIG. 17—OSCILLOGRAMS SHOWING THE ELIMINATION OF OSCILLATIONS IN THE WINDING OF FIG. 16 BY PUTTING 685 OHMS IN NEUTRAL TO GROUND

A similar proof is shown in Fig. 12 where all the oscillations of Figs. 5 and 6 were eliminated by means of a neutral resistance. Both of the above methods of eliminating these disturbing voltages are in agreement with the traveling wave theory.

Another possible method of eliminating reflections in such windings is suggested from the transmission line theory. This scheme consists in tapering the surge impedance of each winding. If each phase of the generator winding were equipped with capacitors to ground throughout the winding in such a way that the surge impedance tapered uniformly from its normal value at the line terminal to zero ohms at the neutral and the neutral grounded, then any voltage wave entering the winding would travel through the winding at some variable speed, its magnitude dropping in proportion to the surge impedance. That is, as the wave traveled through the winding its electrostatic energy of potential would be gradually transformed into electromagnetic energy of current, and on reaching the grounded neutral discharge to ground. There would be no reflection because the impedance to ground is that of the surge impedance at that point. This method of eliminating oscillations is difficult to apply to rotating machinery. Moreover simpler methods are available for accomplishing the same result.

DAMPING OF OSCILLATIONS

There is a number of causes for the damping of the oscillations:

One is the fact that all the oscillations are damped at the rate of the applied wave. In all cases the tail of the applied wave is a capacitance discharge and inherently of the form $E\,\epsilon^{-\beta t}$. This may be referred to as the damping of the axis of the oscillations.

A second cause of the damping is the fact that each time the remaining wave returns to the line terminal a portion of the wave, namely $\left(\frac{2\,Z_1}{Z_1+Z_2}\right)$ per unit is lost to the line Z_1, the balance reflecting in the machine winding Z_2. This damping is best seen by studying the development of Fig. 8 which is calculated on the basis of an infinite rectangular wave and no machine losses. The damping due to this junction loss (see Appendix B) is:

$$\epsilon^{\left(\frac{R_o}{2L_o}\right)t} \qquad (13)$$

Where $L_o = D\,L'$ = total inductance of winding

$$R_0 = Z_2 \operatorname{Log}_e \left\{ \frac{Z_2 - Z_1}{Z_2 + Z_1} \right\} \qquad (14)$$

When $Z_1 = 0$, this damping is zero. When $Z_2 = Z_1$ the entire wave will return upon the line and the damping will be a maximum.

If a resistance R had been placed in the neutral of the winding another damping term would enter similar to Equation (13) by replacing Z_1 with R. Here again we know that if $R = Z_2$ maximum damping will occur, that is, there will be no reflection.

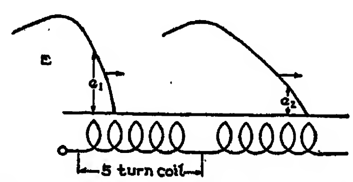

FIG. 18—SCHEMATIC DIAGRAM OF WAVE ENTERING GENERATOR WINDING—SHOWING THE RELATION BETWEEN WAVE FRONT AND VOLTAGE BETWEEN TURNS

A third component of damping follows directly from the fact that the further the wave travels in the machine winding the slower the wave-front becomes. Fig. 12 shows clearly the distortion of the wave as it proceeds through the 6600-volt winding and Fig. 17 for the 2200-volt winding. This distortion may be attributed to natural losses in the winding such as skin effect, leakage, resistance, core losses, and series capacitance between turns. This natural slowing up of the wave-front as the wave proceeds through the winding together with

the fact that slower wave-fronts reduce the oscillations as shown in Fig. 16, accounts for the third component of damping.

Three-Phase Windings

Consider a lightning disturbance to enter on all phases of an n phase machine simultaneously and travel toward the common neutral which is open. Assuming that a voltage wave of E volts travels in each phase of Z_0 ohms surge impedance and that the mutual relations between phases are small, it is desired to determine the maximum neutral voltage. Each wave on arriving at the neutral will find a surge impedance of $\left(\frac{Z_0}{n-1}\right)$ ohms, the parallel value of the remaining phases. The neutral voltage or the voltage wave which enters the remaining phases due to each wave approaching the neutral will be $\frac{2\,E_0}{n}$ and for n phases the maximum neutral voltage will be $2\,E_0$ as in the case of a single winding.

It is now desired to determine the value of resistance R to place in the neutral such that the maximum neutral voltage will be E_0, the lightning arrester voltage. It is shown in Appendix B that this resistance is equal to Z_0/n ohms. This is the parallel value of all the windings to neutral. This resistance in the neutral, equal to one-third the surge impedance of a single winding for a three-phase machine, will not allow the neutral to rise above the terminal voltage. Moreover it will be found that the reflected voltages in each phase due to the wave traveling in that phase are exactly equal and opposite to the transmitted voltage waves from the other phases, and equivalent to no reflection taking place. In this respect a three-phase machine will have the properties of a single winding as discussed and shown in the oscillograms of this paper. Oscillograms taken in three-phase machines under these conditions, and not shown in the paper, bear out these statements.

Protection of Windings

In inductive windings there are two distinct insulations to protect, namely the insulation to ground and the insulation between turns. To protect these insulations properly it is imperative to know just what factors determine the maximum stresses which will occur in the machine to ground and between various sections of the machine winding.

Insulation to Ground (a)

The voltages to ground in practical cases are a direct function of the maximum voltage allowed by the line terminal arrester. The arrester voltage is the applied wave to the machine. However, with an open neutral machine it has been shown that due to reflections of a steep wave at the neutral double arrester voltage occurs in the winding which may cause the insulation to fail.

Consider a special case of a three-phase, 27-kv. machine connected to an overhead line where the lightning arresters allow a maximum of 80 kv. to enter each winding. If the neutral were open the maximum voltage to ground could be 160 kv. or 7.3 times normal crest voltage to ground. This can be reduced to arrester voltage by grounding the neutral, or by placing in the neutral to ground a resistance equal to or less than one-third of the surge impedance of a single winding.

The lightning arrester is essentially a device for the protection of the insulation to ground of inductive windings by limiting the maximum voltage of the wave entering the winding while the neutral resistor is an agent for the protection of the same insulation by preventing positive reflections from taking place at an open neutral. It should be observed, however, that in the protection of the insulation to ground any resistance less than this value may be used.

Insulation Between Turns

Neglecting for the moment the induced voltages in the adjacent turns the voltage between turns for any

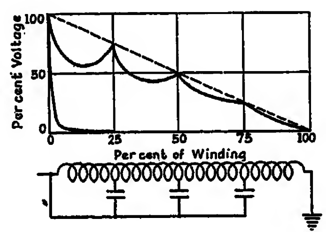

Fig. 19—Effect of Capacity Shielding on Initial Voltage Distributions in Generator Winding

given machine is a function of the steepness of the applied wave. This follows on the assumption that the wave requires a definite time to travel an integral length of the metallic circuit of the winding as indicated on the oscillograms. Consider a steep wave entering the winding of Fig. 18, the wave traveling at a velocity v. When the tip of the wave arrives in the second turn, directly below the point of entering the winding, the voltage between turns will be e_1 volts, which will be smaller with slower fronts. The effect of the induced voltage is always in a direction to lower this maximum stress. As the wave travels through the winding its front becomes slower (see Fig. 12) and hence the maximum stress occurs on the end turns. In case of an open neutral, the steepness of the wave arriving at the neutral doubles when the positive reflection occurs.

Either a steep rise or a sudden drop in voltage may produce high stresses between turns. A steep drop in voltage may be caused by any sudden change of circuit such as an insulation flashover close to the substation. Special means must be employed to reduce these steep gradients. One method which has been developed for inductive windings and found to be very effective in

reducing the stress between turns consists in shielding[9] the winding in such a way that the initial voltage distribution throughout the winding is close to the final voltage distribution. Physically, a continuous shield would be difficult to incorporate in a synchronous machine winding; however, its effect can be very closely approached by placing properly designed capacitors between various points of the winding and the line terminal. Such an arrangement of capacitors would

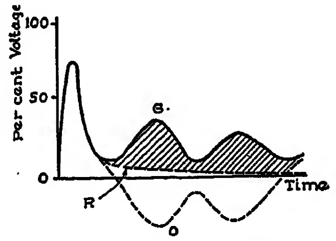

Fig. 20—Typical Curves Showing Voltage between Turns of Generator Winding under Various Terminal Conditions

Voltage between turns
G—Neutral grounded
O—Neutral open
R—Resistance in neutral

change the initial distribution in the generator winding from a continuous distribution curve in which the majority of the voltage drop took place in the first coil to a series of small distribution curves as shown in Fig. 19. This type of shielding is most effective for grounded neutral machines.

Another method is to use a single capacitor to ground in parallel with each lightning arrester. Such a capacitor may be considered as a protective unit for the insulation between turns of inductive windings. Moreover, in slowing up the wave-front of a steep surge the capacitor affords protection to the insulation to ground should it be necessary to operate with an open neutral. This is clearly shown in Fig. 16. In this respect the capacitor to ground at the line terminal in parallel with the arrester can be designed to eliminate practically all the oscillations in an open neutral machine and at the same time to preserve the insulation between turns. It is a very efficient protective unit.

Neutral resistances also play a small part in protecting of the insulation between turns. This follows from the fact that each time the wave reflects in the winding, it subjects the turn insulation to additional strain by increasing the time element. This is readily appreciated by studying the distribution curves of Fig. 13, realizing that the slope of these curves at any point is an indication of the voltage between turns at the point and time measured. Fig. 20 shows the voltage between turns of a representative coil near the line terminal for the three conditions of grounded neutral, open neutral, and with the proper resistance in the neutral to suppress reflections. The shaded area is the reduction in stress which is afforded by the neutral resistor.

9. For references see Bibliography.

Other factors also affect the stresses between turns for a given applied wave, the most important of which are the surge impedance of the incoming line and the resistance of the lightning arrester. These will be discussed in connection with the protective devices.

Lightning Arrester Protection

The lightning arrester is an operator or electric valve. It receives a large incoming surge and together with the surge impedance of the incoming line allows a smaller surge to pass. In this respect the lightning arrester is a very satisfactory agent for limiting the amplitude of voltage wave which enters machine windings. It has no power to prevent oscillations within the winding.

In fact, it is entirely possible to have a wave enter the winding just below arrester breakdown, travel to an open neutral, and reflect positively to practically double arrester voltage, the reflected wave returning to the arrester causing it to go into operation for the first time; but by this time the insulation may have had ample time to fail. Here we see that it is necessary to avoid dangerous reflections at the neutral to limit the internal potentials to arrester voltage, thus crediting the arrester with its true power for protecting the insulation to ground of inductive windings.

Assuming that these precautions are taken the factors controlling the size and shape of the wave entering the winding will be considered for a given lightning surge applied to the terminal. With the advent of thyrite, the new material for lightning arresters,[1] the predetermination of arrester voltages for a given wave and circuit condition are readily obtained by a simple circuit analysis.[2]

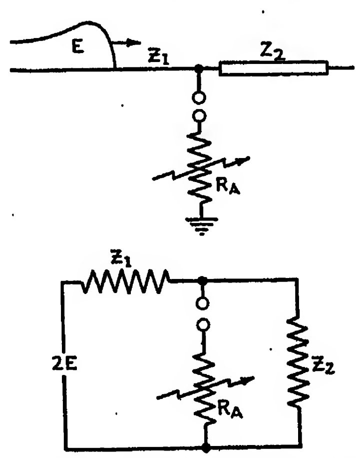

Fig. 21—Equivalent Circuit of Lightning Arrester Protecting a Generator Winding

Applying the general circuit transformation shown in Appendix A to the case of an incoming line of surge impedance Z_1 terminating in a generator winding of surge impedance Z_2, protected by a lightning arrester of resistance R_A the simple lumped circuit of Fig. 21 is obtained. The wave entering the winding will always be identical to the voltage drop across the resistance Z_2

of the lumped circuit when the open circuit wave is applied to its terminals.

This solution of arrester voltage may be divided into three parts, (1) before arrester breakdown, (2) during arrester discharge, and (3) after arrester discharge.

(1) Before arrester breakdown, $\left(\frac{2 Z_2}{Z_1 + Z_2}\right)$ per unit of the traveling wave enters the winding. It is important to observe that the steepness of this wave entering the winding is also increased above the slope of the traveling wave by this same percentage and that it is independent of the lightning arrester.

(2) At a predetermined voltage the arrester goes into operation causing a change in circuit. This sudden change results in a new terminal impedance R_o which is the parallel value of Z_2 and R_A, the arrester resistance, the latter being a variable dependent upon the open circuit voltage. The arrester voltage then suddenly becomes $\left(\frac{2 R_o}{Z_1 + R_o}\right)$ per unit of the traveling wave. This change results in a sudden drop in voltage which is shown in Fig. 22. This drop is independent of the rate at which the voltage rises to arrester breakdown. It will always occur when the arrester goes into operation.

(3) As the voltage drops on the tail of the wave a point will be reached where the arc of the gap goes out and the voltage will suddenly return to the initial curve, or $\left(\frac{2 Z_2}{Z_1 + Z_2}\right)$ per unit of the applied wave. This point will depend upon the arc drop in the gap unit and will correspondingly be a point such that the new voltage will not be sufficient to rekindle the arc. This small rise in voltage may be neglected.

When the arrester goes into operation the terminal voltage will suddenly drop then slowly rise again depending on the crest value of the open circuit wave, coming to a new crest, which in case of a severe wave, may be slightly higher than arrester breakdown voltage. The maximum voltage which a given arrester may attain is hence governed by the insulator flashover value of the line.

In the foregoing relations it will be found that the surge impedance of the incoming line plays a definite part in protecting the winding, in that the larger this surge impedance, the lower the arrester voltage as seen from the relations shown above. The fact that the front of the wave will have had time to penetrate the winding, charging its capacity to a definite voltage before the arrester goes into operation and allowing this stored energy to discharge back through the arrester resistance after arrester operation, will help considerably to lower the stress on the end turns due to the drop in arrester voltage.

Capacitor Protection

In the previous study it was observed: (1) that the arrester before breakdown does not affect the front of an incoming wave, and (2) that the steepness of the wave entering the winding has been increased to $\left(\frac{2 Z_2}{Z_1 + Z_2}\right)$ per unit of the steepness of the incoming wave due to reflection at the change of surge impedance.

The capacitance of substation equipment plays a very small part in protecting terminal apparatus from these steep waves by providing a reservoir for the energy stored by the front of the wave and delivering this energy to the wave should any sudden change in voltage tend to take place. This inherent capacity of the terminal equipment is not sufficient to protect the insulation between turns of machine windings and it becomes necessary to provide additional capacity to reduce steep waves to safe gradients.

Introducing a capacitor in parallel with the arrester of Fig. 21 and assuming the severe case of a rectangular wave of a magnitude equal to the line insulation flash-

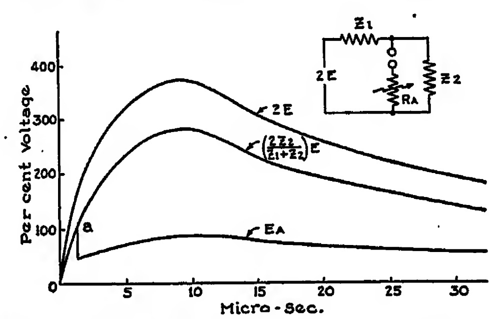

Fig. 22—Typical Form of Arrester Voltage Showing the Drop in Voltage Due to the Arrester Operation

over value for the length of wave considered, the resulting voltage may be determined.

The equation for the front of the wave entering the machine winding will be

$$E_g = \left\{ 2 E \left(\frac{Z_2}{Z_1 + Z_2}\right) \left\langle 1 - \epsilon^{-\left(\frac{Z_1 + Z_2}{C\, Z_1\, Z_2}\right) t} \right\rangle \right\} \quad (15)$$

where E is the insulator flashover value of the line. It follows from this relation that the maximum voltage between turns due to this wave, based upon the time constant of the voltage wave shown in diagram of Fig. 18, and Equation (12), will be:

$$E_T = \left(\frac{2 E\,(1.8\, D + 0.1\, M\, L\, T)\, K\, 10^9 \text{ volts}}{v\, Z_1\, C}\right) \quad (16)$$

Where $t = \frac{l}{v}$

Assuming a velocity of 10,500 miles per second in the slot as found by tests, this relation reduces to:

$$E_T = E \left\{ \frac{3\,(1.8\, D + 0.1\, M\, L\, T)}{Z_1\, C} \text{ volts} \right\} \quad (17)$$

where

E_T = maximum voltage between turns in volts

E = insulating flashover in kv.

Z_1 = surge impedance of incoming line in ohms

C = capacitance to ground in microfarads

D = core length in inches

$$K = \left(\frac{1}{12 \times 5280}\right)$$

$M\,L\,T$ = mean length of turn in inches

At a definite voltage the arrester goes into the circuit, but due to the stored energy in the capacitor the voltage will not drop suddenly but will discharge to the original arrester voltage through the parallel resistance paths afforded by the arrester and adjacent lines. This discharge circuit is shown in Fig. 23 and becomes important in considering the limiting condition of a sphere-gap in place of the arrester. Independent of how slowly the voltage may have risen to gap breakdown with the assistance of additional capacitors to ground, when the gap breaks down all of the stored energy in the capacitor is immediately short circuited to ground, resulting in a sudden drop in voltage. This is excellent protection for the insulation to ground but may increase the stress on the insulation between turns.

In this respect the resistance of the arrester provides

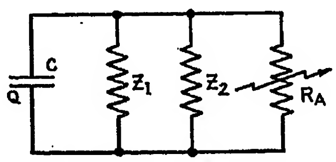

FIG. 23—DISCHARGE CIRCUIT AFTER ARRESTER BREAKDOWN

a discharge circuit with a reasonable time constant, allowing the gradient after arrester breakdown to be within the limits for the protection of the insulation between turns.

Should a flashover occur on the line close to the capacitor the time constant of the resulting discharge circuit would be so small that the stored energy in the capacitor would be of little value in reducing the sudden drop in voltage. The chance of such a flashover near the station is confined to the probability of a direct stroke occurring in this region since any traveling wave will reflect as a negative wave from the arrester.

It has been shown that by slowing up the front of the wave the oscillations can be considerably reduced, thereby effecting protection for the insulation to ground of open neutral machines. By making a close study of Fig. 16 it is found that to obtain the reduction shown in the figure it is necessary to provide a capacitor which would allow a steep wave to rise to arrester breakdown in a time close to the period of the natural frequency of the open circuit winding. The period is given by the equation

$$T = \left\{\frac{4\,N\,l}{v}\right\} \tag{18}$$

where $N\,l$ is the effective length of the winding given in the Table I and v = 10,500 miles per second.

Making this time substitution in Equation (15) and solving for the required capacitance there results the expression

$$C = -\left\{\frac{(Z_1+Z_2)}{Z_1\,Z_2} \Big/ \left\langle \frac{4\,N\,l}{\operatorname{Log}_e\left\{\frac{(Z_2(2-m)-m\,Z_1)}{2\,Z_2}\right\}v}\right\rangle\right\} \tag{19}$$

where

Z_1 = surge impedance of incoming line

Z_2 = surge impedance of winding

m = arrester breakdown in per unit of line insulator flashover

v = velocity of the wave in the winding.

Consider the capacitor required to reduce the oscillations in the 24,000-volt winding when connected to 300-ohm line whose insulator flashover is 450 kv. and the arrester breakdown set at 90 kv. Here m = 0.2. Solving for C it is found that 3.12 microfarads are required to reduce the oscillations. This is considerable capacity and far in excess of that required for the protection of the turn insulation of the same winding, the amount required for this being approximately 0.3 microfarad.

When it is necessary to use line reactors to limit the short-circuit currents they can be employed effectively in connection with the surge protection of the same machine. This is accomplished by properly shunting the reactor with a resistor[8] and using a smaller capacitor to ground than would have otherwise been necessary to produce the same reduction in wave-front. The resistor shunting the reactor is necessary to damp the oscillations between the reactor and capacitor so that the crest valve of the first peak of the oscillations will be well below the strength of the insulation to ground of the machine winding. When the reactor is placed between the capacitor and the lightning arrester it will offer an additional safeguard to the terminal equipment in the event of a flashover near the station. This is evident since such an impedance between the capacitor and the flashover will furnish a circuit with a reasonable time constant allowing any stored energy in the capacitor to become effective in reducing the gradient of the sudden drop in voltage.

Another advantage of the capacitor is that it will permit the location of the lightning arrester further from the terminal apparatus which it is to protect from traveling surges. This is true because it will not allow reflections to build up between the arrester and the apparatus. This will be appreciated when it is realized that the slow wave-front of Fig. 16 was sufficient to prevent oscillations in the generator winding which is equivalent to an open line of 3300 ft.

Other factors must be considered also in the use of capacitors which in certain cases may become quite

important, namely, the effect upon carrier current systems and the circulation of harmonic currents generated by the machine.

Neutral Protection

On a transmission line basis the neutral of a machine winding is several miles from the line terminals. It has also been shown that steep waves traveling on all three phases of Y-connected machine may cause the neutral to rise to twice arrester voltage if the neutral were open. From this standpoint the concept of neutral lightning protection is introduced as a necessary addition to the protection of ungrounded machines exposed to lightning or switching surges.

The ideal neutral protection from the traveling wave standpoint would be a pure resistance to ground equal to the surge impedance of the several phases in parallel. Often such a resistance cannot be used because of short-circuit protection or telephone interference problems. Consider a practical case of three arrester-protected generators in parallel feeding an overhead line, one of the generators being grounded through a very small resistance to furnish current for the short-circuit protection of the group, the other two generator neutrals being left open. The two open neutral machines may be subjected to internal potentials to ground double the maximum arrester voltage while the grounded machine is adequately protected. Should resistors of 200 ohms be put in the neutrals of the two exposed machines the resulting circulating currents may be undesirable. This difficulty is overcome when it is realized that this form of neutral protection is only desired in case of surges, thus permitting the use of any device which will automatically lower the neutral voltage in case of a disturbance entering the winding. A material excellently adapted to this purpose is thyrite.[1] Consider a unit of thyrite properly designed and placed in the neutral to ground of the two open neutral machines. Under normal operation the neutral potential of the machine is low and the corresponding resistance of the thyrite is extremely high, permitting only a few milliamperes of circulating current, effectively an open neutral. Now when the neutral voltage tends to rise due to a disturbing transient reflection the resistance of the thyrite immediately drops. Every time the neutral voltage is doubled the resistance to ground becomes one-sixth of its former value. In this way the neutral protector can be designed to give the proper resistance to ground in the presence of half the lightning arrester potential, thereby affording the desired surge protection and still operating effectively as an open neutral during normal operation.

Consider the case of a large synchronous condenser connected directly to an overhead line, while near by on the same system are several groups of transformers feeding a metropolitan area, the transformer neutrals providing the short-circuit protection of the substation. In case the synchronous condenser has certain harmonics in its wave form it may be desirable to leave the neutral open to avoid interference with the neighboring telephone circuits, at the same time subjecting the insulation to double arrester voltage in case of a steep surge. Should a resistance equal to the surge impedance of the several windings in parallel be placed in the neutral for adequate surge protection, it may be found that the interference currents are still appreciable. These difficulties may be overcome by placing thyrite in the neutral to ground. It will function as in the preceding case in the event of a surge, while during normal operation its high resistance property will allow only a fraction of a milliampere of harmonic currents to flow in the presence of 1000 volts of harmonic voltages at the neutral. In this respect thyrite offers advantages in reducing telephone interference currents.

Many neutral protection devices are possible and might have specific application in certain cases, such as a neutral reactor in parallel with thyrite. Gaps in the neutral preferably are avoided except in cases where there is a reservoir of energy and a discharge circuit with a reasonable time constant to take the shock of the sudden gap operation. The principle here is the same as outlined in connection with the line terminal protection.

It should be restated that whereas a grounded neutral winding will allow a negative reflection to take place, the stress on the insulation to ground will not be in excess of the lightning arrester voltage and for this reason machines operating with solidly grounded neutrals or with a resistance below the parallel value of the surge impedance of the respective phases, should not require any additional neutral protection.

Summary and Discussion

An oscillographic study of the transient oscillations in machine windings has been presented which reveals the following facts:

(1) That machine windings subjected to transient surges function as finite transmission lines of several miles in length obeying the natural laws of reflection and propagation of surges on an open line.

(2) That due to reflections at open neutrals the maximum voltage to ground in a machine winding due to a unidirectional surge is double the maximum arrester voltage.

(3) That the surge impedance of machine winding tested is in the neighborhood of 600 to 1000 ohms while the velocity of propagation of the waves is in the neighborhood of 10,000 miles per second in the slot portions.

The traveling wave analysis of the voltage oscillations has very simply accounted for the following secondary phenomena:

(1) Relations between natural frequency and voltage magnitude in open, ground, and fractional windings.

(2) Phase displacements and harmonic relations between various points in the winding.

(3) Oscillation of voltage distribution curves as standing waves about the final voltage distribution.

(4) Damping of the oscillations.

Three possible methods of reducing the disturbing oscillations in rotating machines were discussed. They are:

(1) Reduction by slowing the front of the applied wave with a capacitor in parallel with the lightning arrester.

(2) Preventing reflections at the neutral by grounding the neutral through the characteristic impedance of the machine windings.

(3) Tapering the surge impedance of each phase from its normal value at the line terminal to a very small value at the grounded neutral.

In the light of the facts made known in this investigation the following conclusions regarding protective equipment were reached.

(1) That the lightning arrester is the most effective protective unit now available for the protection of machine windings. However, it only limits the magnitude of the wave which enters the machine winding and cannot control the oscillations within the winding. It does not affect the front of the wave below arrester breakdown.

(2) Neutral impedance when used can be made of thyrite and effectively be an open neutral during normal operation and yet afford the necessary additional protection in case of a dangerous surge.

(3) Capacitors in parallel with the lightning arrester afford adequate protection for the insulation between turns of machine windings. They also provide protection for the insulation to ground of machine windings by reducing internal oscillations in cases where the neutral is open. In this respect they may even be designed to eliminate the oscillations in short open neutral windings.

(4) The principles of shielding which have proved successful in protecting transformers[9] may also be applied to generator windings.

(5) For the adequate protection of large units connected directly to the line and with neutral open, some protector in addition to lightning arresters is necessary in order to insure that the internal voltages to ground will not exceed the arrester voltage and to adequately protect the insulation between turns.

ACKNOWLEDGMENT

The author wishes to acknowledge the helpful suggestions of Mr. P. L. Alger under whose direction this investigation has been made possible.

Much credit is also due to Mr. C. M. Foust and his assistants Messrs. N. Rohats, H. R. Walker, and others whose help has made possible the oscillographic tests shown in this paper.

Appendix A

The purpose of this appendix is:

(1) To prove that the laboratory test circuit used for obtaining the results shown in this paper is an accurate representation of actual field conditions.

(2) To show that these laboratory circuits are based upon the equivalent lumped circuits of the distributed transmission line field circuits under transient conditions, the latter being rigorously derived and forming a convenient and accurate method of applying simple circuit theory to the calculation of the performance of protective equipment, avoiding completely the introduction of the old traveling wave equations.

The increasing use of high-voltage laboratories for conducting investigations to study the performance of electrical equipment under transient disturbances and for testing the insulation strength of transmission line equipment points to the desirability of the standardization of testing methods. This need will be further appreciated when it is realized that where traveling wave conditions are to be satisfied in the laboratory it not only becomes necessary to obtain voltages which appear to be similar to those found in practise but it is also necessary to satisfy the corresponding current relations. In satisfying both current and voltage relations the complete energy relations of the traveling wave are satisfied and the laboratory results may be used with safety as criterions of field conditions.

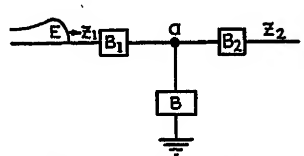

Fig. 24—Generalized Circuit of a Traveling Wave Approaching a Junction Impedance

The ratio of the voltage to current of a traveling wave is defined as the surge impedance of the line and by definition is ohmic in value. This ohmic property of a transmission line to traveling surges is extremely important and should receive a definite place in the equivalent test circuit.

The rigorous derivation of a general equivalent circuit of a transmission line meeting any type of terminal or junction impedance for surge conditions appears in the literature[3] and only the results of this analysis will be given here.

Consider the general circuit of Fig. 24 consisting of two transmission lines with junction impedances B_1, B_2, and B and the wave approaching from the left on the line of surge impedance Z_1.

The impedance B_1 and B_2 may be reactors, series capacitors, etc. while B is the impedance of the terminal equipment to ground.

Using the classical wave equations of traveling waves on transmission lines with which actual line performance has been calculated many times,[3,4,5] it is readily

shown that the expression for the current wave entering the line Z_2 of Fig. 24 for the wave e approaching on the line Z_1, is,

$$i_{v2} = \left\{ \frac{2\,e\,B}{B(Z_1+Z_2+B_1+B_2)+(Z_1+B_1)(Z_2+B_2)} \right\} \quad (20)$$

Now consider the transmission line circuit of Fig. 24 closed into the lumped circuit of Fig. 25 by allowing the surge impedances to have the property of

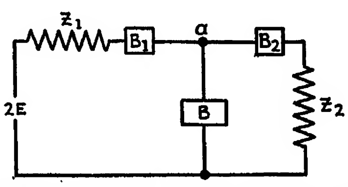

FIG. 25—EXACT EQUIVALENT CIRCUIT OF FIG. 25

lumped resistance equal to the ohmic surge impedance of the respective lines.[13] Solving for the current in Z_2 of this circuit for the application of $2\,e$ or the open circuit voltage on the line, there results the identical equation that was obtained above by the well known, but rarely used, wave equations. In the same way, every voltage and current in the lumped circuit satisfies the classical wave solution to the extent that all transmitted and reflected waves may be computed[3] by the application of Ohm's and Kirchoff's laws to the simple lumped circuit of Fig. 25.

This circuit has been used successfully to calculate the terminal voltages of transformers when used in connection with choke coils and reactors, both with and without lightning arresters, when subjected to traveling waves over the transmission line of the Turners Falls Electric Company during the summer of 1929. The calculations were in excellent agreement with the oscillograph records.[3] This agreement would naturally be expected if the equivalent circuit were correct. The fact that this equivalent circuit is lumped, immediately suggests that it is also readily adapted as a laboratory circuit for conducting other investigations where traveling waves are impressed upon terminal apparatus. Used as a laboratory circuit it naturally follows that the calculations of such laboratory tests would involve the same procedure and results as would be obtained if the investigation had proceeded in the field. This agreement has made it possible to reproduce fields tests in the laboratory repeatedly with the above circuit.

In adapting Fig. 25 as a laboratory test circuit a slight modification is necessary in order to take care of the capacitance of the lightning generator which is always in the circuit. This modification in turn will be handled in a perfectly rigorous manner, which should result in the design of a testing circuit which will satisfy all the time-energy relations of a traveling wave solution.

Examining Fig. 25 it is seen that looking from the terminal impedance back into the equivalent transmission line, a pure resistance equal to the surge impedance of the incoming line, is found. This pure resistance property of the equivalent circuit of Fig. 25 must be satisfied in the equivalent laboratory test circuit. This is uniquely accomplished by employing a well known parallel circuit consisting of the capacitance C of the lightning generator in series with a resistance R_1, this in parallel with a series circuit consisting of an inductance L and resistance R_2. This is shown as the left hand circuit of Fig. 26. This parallel circuit has the property of a pure resistance for all frequencies when $R_1 = R_2 = \sqrt{\frac{L}{C}}$ = resistance of the

(21)

parallel circuit. This property under these conditions avoids any error being introduced because of the necessity of the capacitance of the lightning generator remaining in the circuit after the initial discharge.

The resulting laboratory test circuit is shown in Fig. 26 and will now be considered in detail to show that under transient conditions it functions as an incoming transmission line.

It should be obvious that in designing the left hand circuit of Fig. 26 for an equivalent surge impedance of Z_1 ohms, the following relations are imperative:

$$R_1 = R_2 = R \quad (22)$$

and

$$R_3 + R = Z_1 \quad (23)$$

Moreover, with a given capacitance C in the lightning generator the necessary inductance is predetermined to satisfy the conditions of Equation (21), that is,

$$L = C\,R^2 \quad (24)$$

The discharge of a capacitance, charged to a voltage E_c, can be rigorously determined by solving the cir-

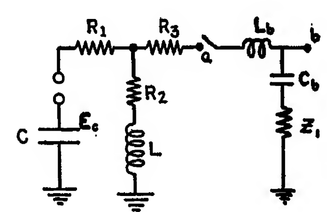

FIG. 26—LABORATORY TEST CIRCUIT WHICH IS THE EXACT TRANSIENT EQUIVALENT OF A TRANSMISSION LINE

cuit as if a battery of E_c volts had been introduced in series with the uncharged condenser.[11] Solving for the open circuit voltage at a of Fig. 27 and letting this voltage be represented by $2\,e$ as in the text of the paper, there results,

$$2\,e = E_c \left\{ \left(\frac{L\,p + R}{L\,p + \frac{1}{C\,p} + 2\,R} \right) \right\} 1 \quad (25)$$

which reduces to

$$2\,e = E_c \left\{ \left(\frac{p^2 + b\,p}{(p+b)^2 + \omega^2} \right) \right\} 1 = E_c\,\epsilon^{-bt} \operatorname{Cos} \omega t \quad (26)$$

Where

$$b = \frac{R}{L} \text{ or } \frac{1}{R\,C} \text{ and } \omega = \sqrt{\frac{1}{L\,C} - (b)^2}$$

However, for the peculiar conditions imposed upon the parallel circuit, ω becomes 0 and the open circuit voltage reduces to

$$2\,e = E_c \left\{ \left(\frac{p}{p+b} \right) 1 \right\} \quad (27)$$

which is recognized[11] as

$$2\,e = E_c\,\epsilon^{-\frac{R}{L}t} \text{ or } E_c\,\epsilon^{-\frac{t}{RC}} \quad (28)$$

Similarly, solving for the current for the case where the terminal a is grounded, simulating a grounded line, there results,

$$2\,i = \left\{ \left(\frac{E_c}{R + R_3} \right) \right\} \epsilon^{-\frac{t}{RC}} = \frac{E_c}{Z_1}\,\epsilon^{-\frac{t}{RC}} = \frac{2\,E}{Z_1} \quad (29)$$

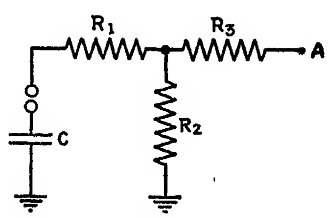

Fig. 27—Laboratory Test Circuit which is a Very Close Approximation of Fig. 27 when the Capacitance C is Relatively Large

Consider the general case of junction impedance $Z_{(p)}$ solving for the terminal voltage there results,

$$E_o = E_c \left\{ \left(\frac{Z_{(p)}}{Z_1 + Z_{(p)}} \right) \right\} \epsilon^{-\frac{t}{RC}} = 2 \left\{ \left(\frac{Z_{(p)}}{Z_1 + Z_{(p)}} \right) \right\} E \quad (30)$$

The above equations are in agreement with the equivalent circuit of Fig. 25 and correspondingly on the transmission line. (See Equation (2).)

The left hand circuit of Fig. 26 is limited in that it will deliver only a wave of rectangular front. This is easily overcome without affecting the surge impedance property of the lightning generator by the addition of the right hand circuit of Fig. 26. This small circuit is designed so that Z_1 satisfies Equation (23) and $\sqrt{L_b/C_b} = Z_1$. When these relations are met the impedance from the new open circuit terminal b to ground is still a pure resistance equal to Z_1, at all frequencies. This small circuit actually subtracts a wave of the form $E_c\,\epsilon^{-\alpha t}$ from the open circuit wave of the original circuit. The expression for the new open circuit wave is:

$$2\,e = E_c \left(\frac{\alpha}{B} \right) \{ \epsilon^{-bt} - \epsilon^{-\alpha t} \}$$

where,

$$\alpha = \frac{1}{Z_1\,C_b} = \frac{Z_1}{L_b}$$

$$b = \left(\frac{1}{R\,C} \right) = \left(\frac{R}{L} \right) \text{ (See Eq. (22))}$$

$$B = (\alpha - b)$$

Such a circuit will permit the wave-front to be modified by altering the constants of the right hand circuit only. The circuit of Fig. 26 has an additional advantage in that the crest value of the open circuit wave is automatically a function of the wave-front in a similar relation to the waves found in practise.

Under all the terminal conditions which can be imposed upon this circuit it will be found to function just as if a transmission line for which the generator is designed were terminating in the laboratory. The validity of the circuit has been demonstrated both mathematically and by actually reproducing field tests in the laboratory, both of which have been readily calculated by the use of the equivalent circuit of Fig. 25.

The use of this circuit will permit the testing of inductive apparatus in the laboratory, reducing to a minimum the possibility of oscillations taking place between the inductance of the apparatus to be tested and the capacitance of the lightning generator. This is clearly seen by a study of Equation (30) and the corresponding circuit for conditions other than imposed by Equation (21).

In the laboratory testing of protective equipment, such as lightning arresters, *to determine the actual reduction in voltage which the arrester will permit*, should the surge impedance property be omitted from the generator circuit the results will be inaccurate. This will be appreciated when it is realized that the fundamental principle upon which the lightning arrester operates is merely the potentiometer principle, the reduction in voltage at the end of an open line being, $\left(\frac{R_a}{Z_1 + R_a} \right)$ per unit of the open circuit voltage where R_a is the arrester resistance (a variable) and Z_1 the surge impedance of the incoming line. Any parallel terminal impedance or extended line will always aid the arrester operation because it merely tends to reduce the equivalent arrester resistance.

Any particular terminal or junction condition can be rigorously set up in the laboratory for tests under impulse conditions by applying the simple principles outlined above. In fact the principles of representing all surge impedance by pure resistance to ground, the line delivering the wave by the proper surge impedance in the peculiar form of the circuit shown in Fig. 26,

each particular case satisfying the equivalent circuit of Fig. 25, makes a very flexible arrangement which can be utilized effectively in carrying on these investigations with laboratory equipment.

For the purpose of tests shown in the text of the paper the test circuit of Fig. 26 was modified slightly with no appreciable loss in accuracy. Owing to the *relatively* large electrostatic capacity of the lightning generator and because the transient impedance of the apparatus to be tested was essentially ohmic, that is, the surge impedance of the respective windings, the inductance of the parallel circuit was omitted. Under these conditions it will be found, by carrying through similar calculations shown above, that the capacitance of the generator will only affect the reflected wave from the neutral of the winding to a slight degree.

The test circuit used is shown in Fig. 27. Here the resistors were designed so that,

$$R_3 + \left(\frac{R_2 R_1}{R_1 + R_2} \right) = Z_1 \qquad (31)$$

where $Z_1 = 250$ ohms, the assumed surge impedance of the incoming line.

The laboratory verification of the circuit is also readily made by studying the excellent agreement of the oscillograms with the corresponding calculations of what would be expected with an actual line of 250 ohms meeting a generator winding of 800 ohms. See also Equation (3).

Since it has been found that natural lightning can produce very steep waves at the terminals of apparatus,[6] the effect of these waves can readily be computed[2] with the aid of the equivalent circuit of Fig. 25, provided the impedance of the terminal apparatus to such surges is known.

During the summer of 1929 it was shown experimentally[7] that externally transformers functioned as capacitors to traveling surges.[10] The failure to detect any impedance in parallel with this capacitance is readily accounted for in that any large ohmic impedance in parallel with the lightning arrester used would only help to reduce the arrester resistance a fraction of one per cent and could not be detected on the oscillograms, and as far as the *external* properties of a transformer are concerned it may be neglected.

The investigation presented in the text of this paper shows that generator windings function as finite transmission lines to such surges but also have a very small capacitance to ground at the line terminal, this capacitance being the small capacitance of the end turns around the winding in parallel with the capacitance of the first few turns to ground. This external capacitance to ground of the generator winding has also been found to produce oscillations with adjacent reactors when the resistance (surge impedance) of adjacent lines would permit. The external equivalent circuit of a generator winding is therefore a small capacitance in parallel with a resistor equal to the surge impedance of the winding.

This information permits one general lumped circuit to be given which will suffice for practically all cases of junction or terminal equipment subject to traveling surges. This circuit is rigorous and includes the impedances of terminal apparatus as determined from tests. It is shown in Fig. 28.

The various parameters are:

Z_1 is a resistance equal to the surge impedance of the line on which the traveling wave E is approaching the substation.

Z_2 is the parallel value of the surge impedances of all outgoing transmission lines on the same circuit.

R_A is the resistance of the arrester protecting the substation.

B_1 is any series element such as reactors or series capacitors.

C is the external capacitance of the substation equipment to ground.

Z_g is the surge impedance of all machine windings in parallel connected to that phase.

$2\,E$ is the open circuit wave or twice the incoming wave. Its maximum value can be twice the insulator flashover value of the incoming line.

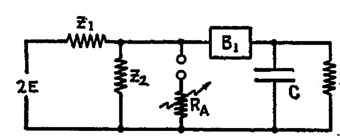

Fig. 28—Generalized Circuit for Calculating the Effect of any Incoming Wave upon any Terminal Equipment

The voltage drop across Z_g is the wave which enters machine windings and which in the case of open neutrals will reflect to double arrester voltage.

This surge impedance Z_g will represent an infinite line when the proper impedances are put in the neutral to ground of each machine winding, otherwise reflections from the neutral would have to be considered.

For the purpose of laboratory tests the circuit of Fig. 28 would be modified by replacing the surge impedance Z_1 and the applied voltage with the test circuit of Fig. 26 designed for the surge impedance Z_1 as outlined above, Equation (23). This constitutes a rigorous analysis of a method of testing any terminal arrangement under transient surges. Where surges enter on more than one line and their combined effects are desired on terminal equipment, simple tests should be made for both and the results properly superimposed.

In Appendix B some interesting equivalent circuits representing generator windings under special terminal conditions will be considered.

Conclusions

(1) Equivalent lumped circuits of traveling wave problems are available which will satisfy all the energy relations of the classical wave equations.

(2) These equivalent circuits are readily adapted as laboratory test circuits and may be used as such to reproduce or extend field investigations pertaining to the problems of protecting terminal equipment from traveling surges.

(3) These circuits are also excellently adapted to the laboratory determination of the equivalent transient impedances of terminal equipment and to study the internal disturbances caused by such surges.

Appendix B

(1) *Damping of Oscillations.* One component of the damping is shown in Fig. 8 to be attributed to the loss of part of the wave to the incoming line. Each time a reflected wave returns to the line terminal $\left(\dfrac{2 Z_1}{Z_1 + Z_2}\right)$ per unit of the remaining wave is lost. The part which returns in the winding is therefore $\left\{\dfrac{Z_2 - Z_1}{Z_2 + Z_1}\right\}$ per unit of the remaining wave.

Consider now the bottom diagram of Fig. 8. Realizing that the damping is exponential, the following relations may be written.

$$\epsilon^{-\alpha t_1} = y_1 \tag{32}$$

$$\epsilon^{-\alpha(t_1+T)} = y_2 \tag{33}$$

But

$$y_2 = \left\{\frac{Z_2 - Z_1}{Z_2 + Z_1}\right\} y_1 = B\, y_1 \tag{34}$$

Substituting (34) in the above equations there results,

$$\epsilon^{-\alpha T} = B \tag{35}$$

from which,

$$-\alpha = \frac{\text{Log}_e B}{T} \tag{36}$$

Now

$$T = \frac{2 D}{v} = 2 D \sqrt{L' C'} = \frac{2 D L'}{Z_2} = \frac{2 L_o}{Z_2} \tag{37}$$

Hence

$$-\alpha = \left\{\frac{Z_2 \text{Log}_e \left(\dfrac{Z_2 - Z_1}{Z_2 + Z_1}\right)}{2 L_0}\right\} = \left(\frac{R_o}{2 L_o}\right) \tag{38}$$

The resulting damping is therefore

$$\epsilon^{\left(\frac{R_o}{2 L_o}\right) t} \tag{39}$$

where $R_o = Z_2 \text{Log}_e \left\{\dfrac{Z_2 - Z_1}{Z_2 + Z_1}\right\}$

and L_o is $D L'$ or the total inductance of the finite winding.

In the case of an open neutral winding $T = \dfrac{4 D}{v}$ and the resulting damping takes place at the rate

$$\epsilon^{\left(\frac{R_o}{4 L_o}\right) t} \tag{40}$$

with the open circuit wave as the reference axis.

(2) *Equivalent Circuit of Generator Winding Under Transient Conditions.* The natural frequency of the open circuited generator winding has been shown (Equation 11) to be

$$f = \frac{1}{4 \pi \sqrt{L C}} \tag{41}$$

Furthermore the oscillograms shown in Fig. 17, have, by inspection, the general form

$$e = E\, \epsilon^{-kt} (1 - \text{Cos}\, w\, t.). \tag{42}$$

These facts suggest that the equivalent circuit of an open circuited generator winding under transient conditions is an inductance in series with a capacitor to ground, the line terminal of the inductance representing the line terminal of the machine winding and the point between the capacitor and inductance representing the open circuited neutral. Such a circuit is only valid, of course, for the approximation of the voltages to ground in the machine winding and for this purpose it may be used to show the effect of various waves and terminal impedances. To include the effect of damping, resistors may be put in series with the inductance.

When a unidirectional voltage E is applied to the terminal of the inductance, the voltage at the neutral will be $e = E\,(1 - \text{Cos}\, w\, t.)$. The voltage at the midpoint of the inductance will be $e = E\left\{1 - \dfrac{1}{2}\ \text{Cos}\ w\, t.\right\}$ which is a close approximation to the voltage at the midpoint of the winding.

The effect of any neutral impedance can be approximated by placing such an impedance in series with the capacitor to ground in the equivalent circuit. Consider a resistance R equal to the surge impedance of the winding placed in the neutral. The resulting neutral voltage will be

$$e = E\left(1 - \epsilon^{-\left(\frac{R}{L_o}\right) t}\right) \tag{43}$$

showing that the neutral voltage will not rise above the applied voltage. The resulting circuit in this case will be found as the right hand circuit of Fig. 26, showing that this small circuit which was used to control the front to the lighting generator wave is actually the transient lumped circuit equivalent of a finite transmission line terminating in its surge impedance.

(3) *Maximum Open Neutral Voltage in the Case of an n Phase Machine.* The maximum transient voltage at the open neutral of an n phase machine will occur when waves of equal magnitude travel in all three phases arriving at the neutral simultaneously.

Consider now that the three phases were isolated, each being protected by a resistor to ground equal to the surge impedance Z_o of the single phase. Now

when a voltage wave E_o travels in each phase simultaneously the corresponding points of the various phases will be at the same potential at each instant, allowing the neutrals of the respective phases to be electrically connected without affecting the voltages. The resulting resistance to ground will, therefore, be Z_o/n. This analysis neglects the induced voltages in the various phases which will tend to make the surge impedance of the three phases in parallel less than one-third of the surge impedance of a single phase.

References

1. *Thyrite—A New Material for Lightning Arresters*, by K. B. McEachron, A. I. E. E. Quarterly TRANS., Vol. 49, April 1930, p. 410.

2. "Performance of Thyrite Arresters for Any Assumed Form of Traveling Wave and Circuit Arrangement," by K. B. McEachron and H. G. Brinton, *General Elec. Rev.*, June 1930.

3. "Calculation of Voltage Stresses Due to Traveling Waves, with Special Reference to Choke Coils," by E. W. Boehne, *General Elec. Rev.*, Dec. 1929.

4. "Reflection of Transmission Line Surges at a Terminal Impedance," Otto Brune, May 1929, p. 258.

5. *Traveling Waves Due to Lightning*, L. V. Bewley, A. I. E. E. Quarterly TRANS., Vol. 48, July 1929, p. 1050.

6. *Symposium on Lightning Investigations*, A. I. E. E. TRANS., Vol. 49, July 1930.

7. "Cathode Ray Oscillographic Study of the Operation of Choke Coils on Transmission Lines," by K. B. McEachron, *General Elec. Rev.*, Dec. 1929, p. 668.

8. *Shunt Resistors for Reactors*, F. H. Kierstead, H. L. Rorden, and L. V. Bewley, A. I. E. E. TRANS., Vol. 49, July 1930.

9. *Effect of Transient Voltages on Power Transformer Design*, by K. K. Palueff, A. I. E. E. Quarterly TRANS., Vol. 48, July 1929, p. 681.

10. *Abnormal Voltages Within Transformer Windings*, by L. F. Blume and A. Boyjian, A. I. E. E. TRANS., 1929.

11. "Operational Circuit Analysis," by V. Bush, John Wiley and Son.

12. "Transmission Circuits for Telephone Communication," by K. S. Johnson, Van Nostrand and Company, Inc.

13. "*Excess Voltages and Excess Voltage Prevention*," by W. Peterson, *E.T.Z.*, March 6, 1913, pp. 267-272.

Discussion

EFFECTS OF LIGHTNING VOLTAGES ON ROTATING MACHINES AND METHODS OF PROTECTING AGAINST THEM

(FIELDER AND BECK)

VOLTAGE OSCILLATIONS IN ARMATURE WINDINGS UNDER LIGHTNING IMPULSES

(BOEHNE)

K. B. McEachron: The papers by Messrs. Fielder and Beck and by Mr. E. W. Boehne indicate the same general trend in forms of protection of rotating machines, which are subject to lightning voltages.

Fortunately it is now possible to make accurate calculations relating to arrester performance, either alone or in combination with capacitors as suggested by Mr. Boehne for protection of rotating machinery. This method of calculation is shown i[illegible] Fig. 1 in which any assumed form of applied wave with respe[illegible] to voltage and current is plotted as shown in the curve marked $2\,E_1$. The assumed form of the traveling wave is plotted with double voltage values at the left of the figure and is marked, "Voltage without arrester." This is the voltage which would be measured at the end of the line without the arrester.

Underneath the open circuit volt-time curve is the volt-time curve of the arrester during discharge, which is obtained in the following manner.

The straight line E_a at the right is the arrester characteristic, while $Z_1\,I_a$ represent the product of assumed surge impedance (Z) of the line and any arrester current (I_a) which may flow. These two curves are added together for each value of current giving the curve marked $E_a + Z_1\,I_a$. To determine the arrester voltage and arrester current for any given value of applied voltage as at A, first find the arrester current I_a from

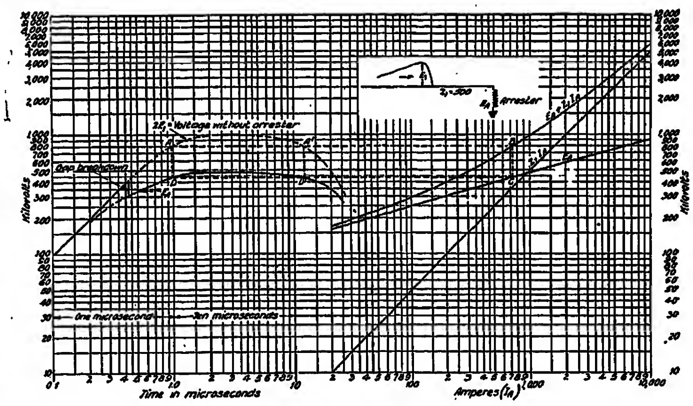

FIG. 1—CALCULATION OF THYRITE ARRESTER PERFORMANCE FOR GROUNDED-NEUTRAL CIRCUIT (115-KV. THYRITE ARRESTER AT THE END OF THE LINE)

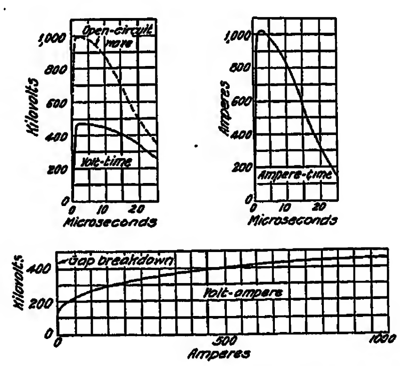

FIG. 2—THYRITE ARRESTER PERFORMANCE CURVES

the curve $E_a + Z_1\,I_a$ for that applied voltage as at B and then find the arrester voltage from the curve E_a as at C. The values for E_a for each value of $2\,E_1$ are plotted against time as the arrester characteristic. From a curve, such as shown in Fig. 1, all of the arrester characteristics may be obtained for any assumed wave, line condition or arrester connection. Such a set of curves appear in Fig. 2 for the case calculated in Fig. 1.

A similar method is shown in Fig. 3 for the combination of a Thyrite arrester and a capacitor[illegible] For the calculation, a 23-kv. arrester in parallel wit[illegible]itor having an electrostatic capacity of 0.1 micro[illegible]nected at the end of a line having a surge impeda[illegible]ms. A perpendicular wave front is assum[illegible] rep[illegible] worst conditions from the [illegible]in[illegible]ront[illegible]e crest potential of the traveling [illegible]tion will depend on the insulation of the

incoming circuit. In Fig. 3 this crest voltage was taken as 250 kv. Using the equation

$$E_c = 2\,E_1 \frac{Z_2}{Z_1 + Z_2}\,[1 - \epsilon^{-\alpha t}]$$

Where Z_2 is the surge impedance of any outgoing lines and $\alpha = \dfrac{Z_1 + Z_2}{Z_1\,Z_2\,C}$ the voltage rise across the capacity with respect to time is obtained. When the arrester is connected in parallel the curve E_{ac} is obtained, which is the protective characteristic of the combination of arrester and capacitor. Such a calculation can be readily made for any assumed set of conditions and the protection determined.

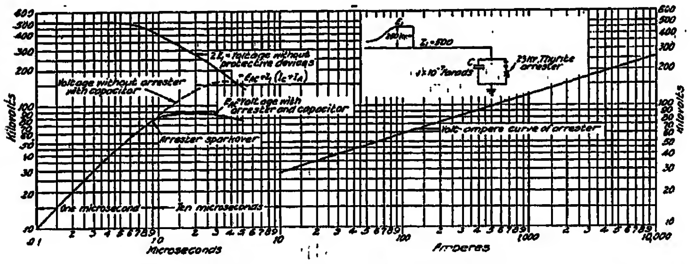

FIG. 3—CURVES FOR THE CALCULATION OF PERFORMANCE OF THE ARRESTER-CAPACITOR COMBINATION

Fig. 3 illustrates how the capacity modifies the wave front of the incoming wave and shows the arrester reducing the voltage across the capacitor to a safe value for the connected machine. Thus both turn to turn insulation and the major insulation to ground are properly protected.

L. V. Bewley: Mr. Boehne's investigation has shown that:

a. The internal oscillations in the windings of rotating machines are primarily due to successive reflections of traveling waves, and are substantially the same as those occurring on a transmission line of finite length.

b. These oscillations may be eliminated by grounding the winding through a resistance equal to its surge impedance, as is evident from traveling wave theory and the oscillographic results obtained.

c. The gradient along the winding, and therefore the turn-to-turn stress, depends on the steepness of the wave front, and is doubled at a total voltage reflection point.

d. The severity of oscillations is decreased by slowing up the wave front, and for a wave front equal to the natural period of oscillation of the winding the oscillations are completely eliminated.

e. An abrupt tail, such as caused by an insulator flashover, is as bad as an abrupt front.

f. The surge impedance of the transmission line has considerable influence on the character of the oscillations in the machine windings, not only with respect to the initial incident wave, but also due to the "junction damping" associated with the successive reflections.

While it is evident from the mass of experimental data which Mr. Boehne has obtained and analyzed that the internal oscillations in the windings of rotating machines are largely traveling wave phenomena, yet a casu[redacted]ination of the oscillograms which he has presented show[redacted]pacitance and mutual inductance are also present[redacted]enced by the considerable distortion of wave sha[redacted] by [redacted]waves entering the winding, and the building[redacted] in excess of values which would be [redacted] pure traveling waves. For instance, in [redacted] paper, referring to a grounded neutral mac[redacted] at a point 10.7 per cent from the line end reaches a potential of 117 per cent, or 17 per cent higher than is possible with pure traveling waves. In this same figure the applied wave has a front of about 5 microseconds but after traveling half way through the winding it has been increased to 15 microseconds. All of the other oscillograms in the paper exhibit these same irregularities, to a greater or less extent.

In view of these differences it is of interest to consider the effects of series and shunt capacitances, self and mutual inductances, and losses on the character of the oscillations in ideal machine circuits. Four typical cases will be considered, on the assumption of a suddenly applied d-c. voltage E. The response to an applied wave of any shape is obtainable from the solution corresponding to the infinite rectangular wave, through an application of Duhamel's theorem or other means of superposition.

The four typical cases are:

1. (L, C_g). Circuit consisting of uniformly distributed series inductance L, and shunt capacitance C_g. This is the ideal transmission line, without losses.

2. (L, C_g, C_s). Circuit consisting of uniformly distributed series inductance L, shunt capacitance C_g and series capacitance C_s. This is sometimes erroneously used as an approximation to the high frequency circuit of the transformer.

3. (M, C_g). Circuit consisting of uniformly distributed mutual inductance M (linearly graded), and shunt capacitance C_g.

4. (M, C_g, C_s). Circuit consisting of uniformly distributed mutual inductance M (linearly graded), shunt capacitance C_g, and series capacitance C_s. This is the circuit of an ideal transformer, and suffices for the analytic description of transformer high frequency oscillations.

The potential e at any point x of the circuit measured from the grounded end, and time t, for any of the above circuits is given by equations of the same form:

$$e = E\left(\frac{x}{l} + \sum_1^\infty B_s \frac{2\cos s\pi}{s\pi} \sin\frac{s\pi x}{l} \cos\omega_s t\right) \qquad (1a)$$

$$= E\left(\frac{x}{l} + \sum_1^\infty B_s \frac{\cos s\pi}{s\pi}\left[\sin\left(\frac{s\pi x}{l} + \omega_s t\right) + \sin\left(\frac{s\pi x}{l} - \omega_s t\right)\right]\right) \qquad (1b)$$

$$= E\sum_1^\infty \frac{2}{\pi s}\Big[B_s \cos(s\pi - \omega_s t) - \cos s\pi\Big]\sin\frac{s\pi x}{l} \qquad (1c)$$

The initial distribution, found by substituting $t = 0$, is

$$e_{t=0} = E\sum_1^\infty (B_s - 1)\frac{2\cos s\pi}{s\pi}\,.\,\sin\frac{s\pi x}{l} \qquad (2)$$

The final distribution, after the oscillations have died away, is

$$e_{t=\infty} = E\frac{x}{l} = -E\sum_1^\infty \frac{2\cos s\pi}{s\pi}\,.\,\sin\frac{s\pi x}{l} \qquad (3)$$

where the infinite series expression is the Fourier expansion of (x/l) between the limits $x = 0$ and $x = l$. Of course Equations (1) do not reduce to (3) on substituting $t = \infty$, because Equations (1) were derived on the assumption of zero losses. Actually, however, there will always be losses present, so that eventually the oscillations will die away.

Each space harmonic of order s in Equation (1b) has a velocity of propagation

$$v_s = \frac{l\,\omega_s}{s\pi} \qquad (4)$$

[redacted]The amplitude B_s, angular velocity ω_s, linear velocity v_s, [redacted]itial and final distributions and the type of propagation, for

each of the four cases under consideration are given in the following table, where $\alpha = \sqrt{C_g/C_s}$.

Case	1 (L, C_g)	2 (L, C_g, C_s)	3 (M, C_g)	4 (M, C_g, C_s)
B_s	1	$\frac{\alpha^2}{s^2\pi^2+\alpha^2}$	1	$\frac{\alpha^2}{s^2\pi^2+\alpha^2}$
ω_s	$\frac{s\pi}{\sqrt{L C_g}}$	$\frac{s\pi}{\sqrt{L(C_s s^2\pi^2+C_g)}}$	$\frac{s^2\pi^2}{\sqrt{M C_g}}$	$\frac{s^2\pi^2}{\sqrt{M(C_s s^2\pi^2+C_g)}}$
v_s	$\frac{l}{\sqrt{L C_g}}$	$\frac{l}{\sqrt{L(C_s s^2\pi^2+C_g}}$	$\frac{s\pi l}{\sqrt{M C_g}}$	$\frac{s\pi l}{\sqrt{M(C_s s^2\pi^2+C_g)}}$
$e_{t=0}$	0	$\frac{\sinh \alpha x/l}{\sinh \alpha}$	0	$\frac{\sinh \alpha x/l}{\sinh \alpha}$
$e_{t=\infty}$	x/l	x/l	x/l	x/l
Type of propagation	As a rigid distribution	High harmonics behind	High harmonics ahead	High harmonics ahead

It may be remarked that the hyperbolic *sinh* expressions for the initial distributions are obtained by recognizing them as the appropriate functions corresponding to the Fourier series of Equation (2). They can also be found by solving the C_s and C_g circuit, since at the first instant no current flows through the inductances, and therefore the initial distribution is completely determined by the capacitance circuit. Still another way of obtaining these expressions for the initial distribution is to substitute $p = d/dt = \infty$ in the operational equations from which the solutions given here were derived.

In cases 2 and 4 the amplitudes of the space harmonics are completely determined by the capacitances C_g and C_s. In fact, these amplitudes are the coefficients of the Fourier analysis of the initial distribution with respect to the final. If

$$\alpha = \sqrt{C_g/C_s} \rightarrow 0 \tag{5}$$

then $B_s \rightarrow 0$ and the oscillations disappear. The basic principle of all methods of electrostatic shielding by means of auxiliary capacitance is to bring about the condition of Equation (5); either by reinforcing the series capacitance C_s or by nullifying the shunt capacitance C_g. Thus if $\alpha = o$ the initial and final distributions are the same, and there are no oscillations.

From Equation (1c) and the values given in the table under case 1, there is

$$e = \sum_1^\infty \frac{2}{s\pi}\left[\cos s\pi\left(1 - \frac{1}{\sqrt{L C_g}}\right) - \cos s\pi\right]\sin\frac{s\pi x}{l}$$

$$= \sum_1^\infty \frac{2}{s\pi}\left[\cos\frac{s\pi y}{l} - \cos s\pi\right]\sin\frac{s\pi x}{l} \tag{6}$$

where $$Y = \left(l - \frac{l}{\sqrt{L C_g}}\,t\right) = (l - v\,t) \tag{7}$$

But (6) is the Fourier series of a rectangular wave which has penetrated the winding to a point distance y from the neutral. When this wave reaches the neutral it reverses and returns to the line end of the winding. The cycle is then repeated. This is the only case in which pure wave motion is present. Thus there are three ways of looking at the phenomena of oscillations in an (L, C_g) circuit, corresponding respectively to Equations (**1a**), (**1b**), and (**1c**) as follows:

Eq.	Point of view
1a	(Fixed distribution) + (harmonic standing waves)
1b	(Fixed distribution) + (pairs of harmonic traveling waves)
1c	(Simple traveling wave)

The only effect of the inductance is in determining the angular velocities ω_s of the space harmonics, and the corresponding linear velocities v_s. If the inductance is purely self-inductance, the harmonics vibrate as their order, but if mutual inductance (linearly graded) is in the circuit the harmonics vibrate as the square of their order.

The presence of either mutual inductance or series capacitance will cause the harmonics to vibrate at such rates as to present the possibility of an eventual piling up of the harmonics in time phase, so as to cause abnormal voltages at points in the winding, in excess of the terminal voltage. The mutual inductance is generally more dangerous in this respect than the series capacitance, since the piling up can occur on the first oscillation of the fundamental, and before the effect of losses or of a decreasing applied wave are seriously felt.

Losses in the circuit, due to series or shunt resistance, have two different effects. First, they introduce a decrement factor for each harmonic causing it to be damped out; and second, they slow down, or even actually prohibit, the rates of harmonic vibration. As a rule, the losses do not exert an appreciable influence on the first complete oscillation of the fundamental and therefore cannot be depended upon as any protection to the machine.

C. W. Guth: A series of tests were made on turbine generator armature coil insulation to determine the ratio of the dielectric breakdown strength of the insulation when tested with an impulse voltage to the dielectric breakdown strength of the insulation when tested at 60 cycles.

Several bars were insulated with micarta folium insulation for use in these tests. The bars were made from a number of copper straps, each of which was mica taped, and represented a section of the slot portion of an armature coil for a 94,200 kv-a., 13,800-volt turbine generator. The bars were approximately 100 in. long and were wrapped with the standard thickness of micarta folium which is used for 13,800 volt generators. A number of condensers was built up at each end of the bars by using treated cloth tape with tin foil applied at definite locations. The purpose of the condensers was to shield the bar and prevent flashover to the ends of the bar during test.

The bars were tested as follows:

1. A surge voltage of 40 kv. was applied and 10 shots were made in succession. All the surge voltage tests were made with a 2 microsecond wave.

2. A voltage of 20 kv. at 60 cycles was applied momentarily to check for failure. This voltage is approximately equal to 1.5 times the operating voltage of the machine.

3. A surge voltage of 60 kv. was applied and 10 shots made in succession.

4. The 60 cycle test at 20 kv. was then repeated.

5. The impulse tests were then repeated, increasing the voltage in steps of 20 kv. up to 160 kv., followed by steps of 10 kv. above this voltage. Ten shots of the impulse voltage were applied at each voltage. The impulse tests at each voltage were followed by the 60-cycle, 20-kv. test, to check for failure.

Two of the bars were broken down under impulse voltages of 160 kv. and 170 kv. respectively. The other two coils which were tested withstood a test of 190 kv., which was the limit of the testing set. These coils were then tested with 60 cycle voltage and failure occurred at 92 kv. and 70 kv.

The bars were re-insulated with micarta folium, and a 60-cycle voltage test was then applied, the voltage being raised until failure occurred. Breakdown occurred at 100, 120, 120 and 140-kv. respectively.

The results of the tests indicate a ratio of impulse breakdown to 60 cycle breakdown of approximately 1½ to 1. However, the impulse tests should be considered in the nature of an endurance test as the insulation was subjected to a large number of tests at the lower voltages before final breakdown occurred. The ratio

of the impulse breakdown value to the operating voltage is approximately 13 to 1.

The extent to which the insulation was weakened is illustrated by the 60-cycle breakdown values obtained on the bars which had previously been subjected to impulse tests compared to those which had not been previously tested, *i. e.*, 80 kv. average breakdown against 120 kv. However, it should be noted that the insulation still shows good dielectric strength, even after a large number of impulse tests was applied.

K. K. Paluef: In February 1919, Messrs. Blume and Boyajian presented to the Institute what I previously described as a classic theory of principles governing the voltage oscillations within transformer windings.

Mr. Boehne presents in his paper, what can be called a classic theory of transient voltage oscillations within generator windings. He has done it in a very clear and convincing manner.

It is hoped that in the near future he will completely cover the subject by presenting results of his studies on voltage distribution found in separate coils of the winding and also on the effect of the presence of the rotor.

In studying the effect of the rotor, I believe it would be of interest to make tests with the rotor in different angular positions. Furthermore, these studies should cover cases where only one out of three phases is subjected to a surge, as in such a case the effect of the rotor should be essentially different from that found with all three phases simultaneously subjected to a surge.

It appears to me that the presence of the rotor should also have an effect on the surge impedance of the machine, and if so, the surge impedance would become a function of angular position of the rotor. It also should be expected that the natural period of oscillation is affected by the rotor.

If all of the above suppositions prove to be correct, the reduction of transient voltage stresses by neutral resistance, equal to surge impedance of the machine, would become more complicated and on the whole, probably less effective.

Furthermore, even under conditions of the test discussed in this paper, the neutral resistance is not as effective as it may appear at first. This happens because in case of simultaneous surge on all three phases the proper value for the neutral resistance is one-third of the value required in case of only one phase subjected to a surge. The latter value cannot be secured as two idle phases in effect are connected in parallel with the neutral resistance. Their combined value is one-half of the surge impedance of one phase, while the total value required for resistance (or surge impedance) at neutral end of the phase that is struck is equal to the surge impedance. Therefore, appreciable oscillations will be present either in one case or the other. It cannot be depended upon that in service all three phases will be always simultaneously subjected to a surge.

It is also essential to consider not only single traveling waves, but also damped oscillations produced by various causes in transmission systems. While their magnitudes are much lower than those of lightning, the effect of successive cycles is cumulative, and therefore equally dangerous stresses may be produced in the winding with much lower applied voltages.

Protection of Generators Connected Directly to Overhead Transmission Lines

The protection of a generator is a far more difficult problem than that of a transformer.

Far greater responsibility is placed on devices protecting a generator than on those protecting a transformer. This is because the impulse ratio of dry insulation used in generators is about one-third of that of the transformer insulation, the cost of the generator per kv-a. is about six times that of the transformer while repairing of the generator takes materially more time and is more expensive. In addition the low voltage transmission lines are generally so much overinsulated in comparison with the insulation strength of generators that there is little hope of co-ordination of the two.

It follows that devices suitable for protection of generators must be considerably more than a usual arrester or arrester and condenser, as they are called upon to reduce the incoming wave not to 50 per cent but to 10 per cent or less, and also to protect against oscillatory transients.

Taking all of the above into consideration, it appears that the protective device must form an impervious barrier between the

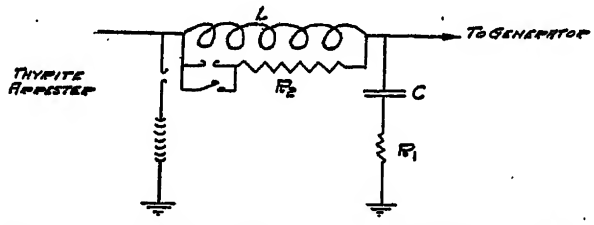

Fig. 4—Protector Against Transient Voltages

line and the generator for voltage transients originated on the line. Such a device which was developed quite some time ago is shown on Figs. 4, 5, 6. Its action is based on the principle described in the author's paper of January 1929. In accordance with this principle, the high frequency voltage will distribute uniformly throughout an inductive winding when an incident wave has both front and tail at least as long as the natural period of the winding. I am glad to find that Mr. Boehne as well as Messrs. Fielder and Beck approve of this principle.

The constants of the devices are so proportioned that the incident wave is modified so that the shape of its front and tail satisfy the above requirement while its crest is reduced to a

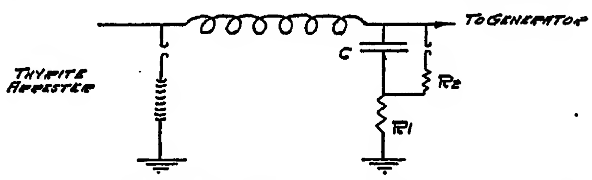

Fig. 5—Protector Against Transient Voltages

predetermined safe value. It will do this even without assistance of the arrester. The arrester is used because by chopping the wave it allows a use of a smaller inductance and capacitance. Therefore, in some cases, the use of an arrester was found economically justifiable. Similar economic advantages may be obtained by proper co-ordination of the strength of adjacent line insulation and of the size of the inductance and the capacitance.

The resistances are inserted for elimination of the possibility of resonance of the inductance and capacitance with other parts of the system or with the harmonics of operating frequency. It appears that this protective scheme is often cheaper with a

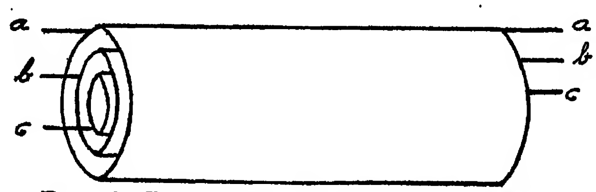

Fig. 6—Three-Phase Interwoven Reactor

relatively high inductance. To permit the use of such an inductance (some 15 per cent of the generator capacity) without appreciably increasing the impedance for the load current, the three reactors of the three phases are interwound so that the impedance to the balanced load current can be made as small as desired. The reactor is oil immersed and its insulation strength is co-ordinated with the adjacent line insulation. The device

thus serves as protection not only against transient voltages, but also against excessive currents in case of a single phase short circuit.

Traveling vs. Standing Wave Oscillations of Inductive Windings

The oscillograms of free voltage oscillations of transformer and generator windings are at first glance so similar that it may be easily supposed that they illustrate identical phenomena.

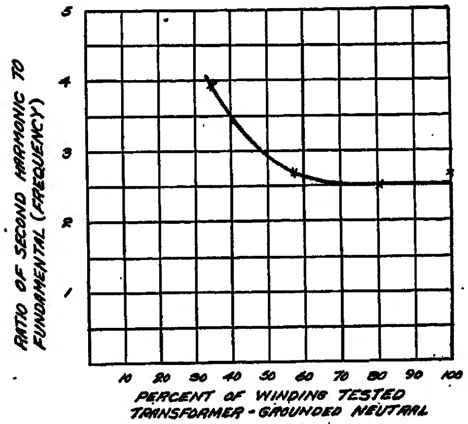

Fig. 7

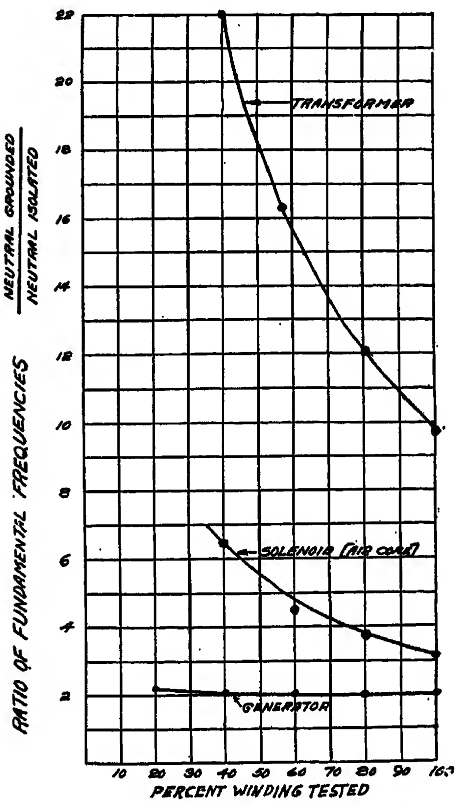

Fig. 8

However, more careful scrutiny indicates that the two phenomena are essentially different. Transformer oscillations consist of oscillations of a number of standing waves, the transformer winding serving as the base or line of equilibrium. Generator oscillation, as Mr. Boehne demonstrated in his paper, consists essentially of a traveling wave surging back and forth in the winding.

The difference between the two oscillations can be stated as follows: When one terminal of a transformer winding is struck by a wave with steep front, the internal oscillation produced thereby starts *simultaneously throughout* the winding. In the case of a generator, these oscillations develop *progressively along* the winding, beginning at the terminal that is struck by the wave.

This difference is not only of academic interest but is also of practical importance. It is responsible for the appreciable difference in magnitude and distribution of high frequency voltage stresses found in the two kinds of windings. The time is too limited to allow detailed discussion of it here, but the

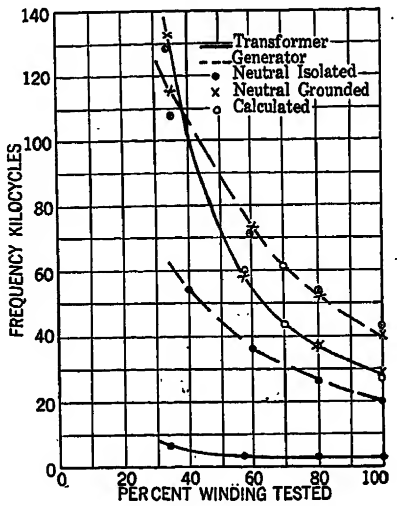

Fig. 9

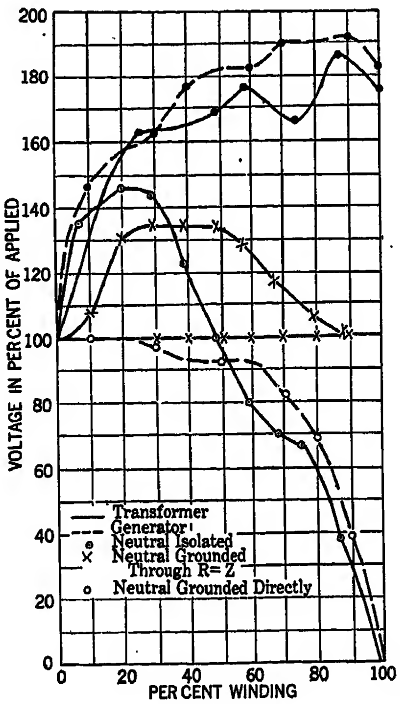

Fig. 10

difference in the effect of neutral resistance on the oscillations can be taken as an example. In case of a generator, a neutral resistance equal to its surge impedance eliminates oscillations, as Mr. Boehne has illustrated, but it does not eliminate them in a transformer grounded through a resistance equal to its, so called, surge impedance.

The oscillation in a transformer develops *simultaneously*, principally due to the presence of high mutual inductance between all parts of the windings. The flow of any current along conductors of the turns near the line end immediately creates a magnetic flux which induces voltages of various magnitudes and phase angles throughout the winding. Therefore, the speed of propagation of the disturbance from one end to the other is equal to the speed of propagation of magnetic flux along the transformer core. The core leg covered with winding is generally

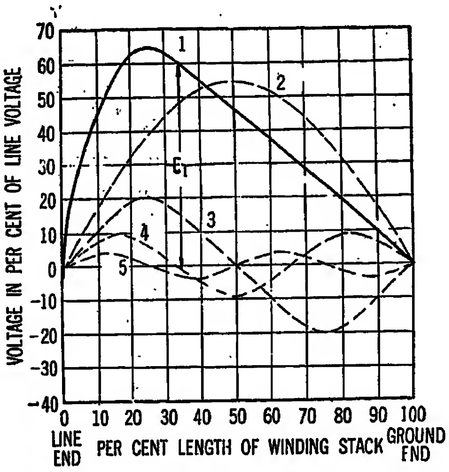

FIG. 11A

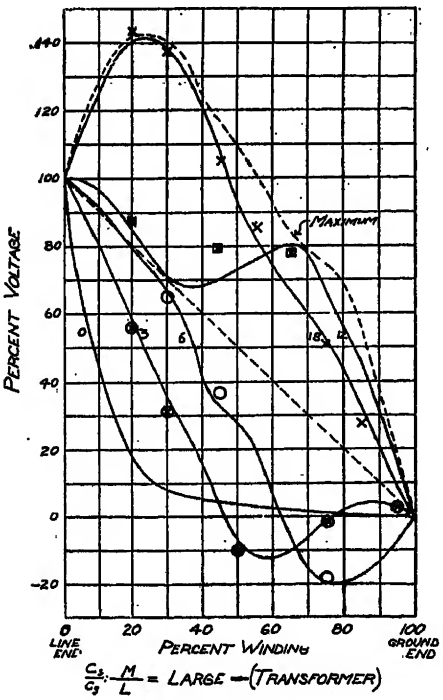

FIG. 11B

only a few feet long, therefore, for all practical purposes, it can be said that the oscillation starts simultaneously throughout the winding. The immediate transmission of disturbance from one end to the other is also facilitated by the presence of the series capacitance between all adjacent coils of the winding from end to end.

It is quite obvious that in a generator the mutual inductance between coils is very much smaller than in a transformer, particularly between the end and the middle coils, with the rotor either removed or bearing a short *circuited winding*.

The series capacitance, (that is, the capacitance from coil to coil) is absent between parts imbedded in iron and is small between the remaining parts.

Under such conditions, the only way a high frequency disturbance can be transmitted to the parts of the winding "electrically removed" from the line end coil is by progressive movement from coil to coil through connections between the coils, very much like propagation of a traveling wave along a transmission line.

However if coils consist of a number of turns, then, since the mutual inductance and capacitance between the turns of the same coil is appreciable, each coil acts like a transformer winding.

A generator then can be looked upon as a chain of transformer windings connected by very short transmission lines. Its oscillation would consist of internal coil oscillation in its nature, approaching that of the transformer windings and of the oscillation of the windings as a whole, which is similar to that of a transmission line.

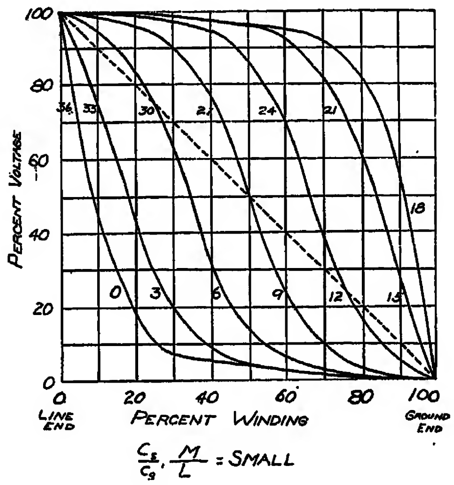

FIG. 11C

Since most of the generator coils have but few turns, only traveling waves with exceeding steep front or tail are able to produce internal coil oscillations.

COMPARISON OF CHARACTERISTICS OF STANDING AND TRAVELING WAVE OSCILLATIONS

The oscillation following the laws of traveling wave differ from that governed by the laws of standing wave in the following respects. Let:

f_{1i}, f_{2i}, f_{3i} etc. and f_{1g}, f_{2g}, f_{3g} etc. be frequency of the first, second, third, etc. harmonics of oscillation of winding with natural isolated and grounded respectively.

Z surge impedance of the winding.

f_{1ip}, f_{1gp} is frequency of the first harmonic of portion p of the entire winding with neutral isolated and grounded respectively.

E_o crest of rectangular traveling wave applied to the winding.

L self-inductance of winding element.

M Mutual inductance between adjacent elements.

C_s capacitance between adjacent elements.

C_g capacitance between element and ground.

The figures referred to below are based on test results. Data

on generators are taken from Mr. Boehne's paper. Data on transformers are taken from the author's investigations.

Then:

	In case of	
	Traveling wave	Standing wave
a.		
$f_{1i} : f_{2i} : f_{3i}$	1 : 2 : 3	more than 1 : 2 : 3 1 : 4 : 8 for example
$f_{1g} : f_{2g} : f_{3g}$ (Fig. 7)..	1 : 2 : 3	more than 1 : 2 : 3
b.		
$f_{1i} : f_{1g}$ (Fig. 8).......	1 : 2	more than 1 : 2 (particularly with iron core) 1 : 22 for example
c.		
$f_{1i} : f_{1ip}$ (Fig. 9)......	p	Within a wide range practically unity
d.		
$f_{ig} : f_{igp}$ (Fig. 9)......	p	less than p $p^{1.5}$ for example
e.		
Maximum voltage to ground throughout winding with neutral grounded directly (Fig. 10)...........	E_o	more than E_o 1.43 E_o for example
f.		
Maximum voltage to ground throughout winding with neutral grounded through $R = Z$ (Fig. 10)......	E_o	more than E_o 1.35 E_o for example

The above difference is due to the fact that in case of a traveling wave the phenomenon is dominated by L and C_g as $\frac{M}{L}$ and $\frac{C_s}{C_g}$ are negligible, while where M or C_s, or M and C_s are appreciable with $\frac{M}{L}$ and $\frac{C_s}{C_g}$ large the standing wave phenomenon dominates. These considerations allowed the present author to construct the "spectrum" of high frequency equivalent circuits published in his paper of last May and reproduced as Fig. 12 here. Mr. Boehne thus found that generators, under the test conditions used, act like circuit No. 2.

It is interesting to note that the ratio of frequencies of harmonics ($f_1 : f_2 : f_3$, etc.) is of fundamental importance.

The frequency of harmonics, in the case of a standing wave, increases faster than the first power of their order, because the presence of C_s and M facilitates direct transmission of energy to distant parts of the winding.

This is illustrated by Fig. 11A where No. 1 of A is "initial voltage distortion" curve and No. 2, 3, etc. its harmonics (space harmonics) as found in *a certain transformer* tested by the author. If each of the above harmonics is made to oscillate with its frequency found in the transformer, then the simultaneous voltage distribution throughout the winding at 0, 3, 6, etc. microseconds after the impact will be as shown by corresponding curve on B of Fig. 11B. Should ratios of frequency of the same harmonics (without change of their amplitudes) be made to correspond to their order ($f_1 : f_2 : f_3 = 1 : 2 : 3$), as the traveling wave phenomenon demands, the simultaneous voltage distribution would be as shown on C of the same figure.

It is obvious that the latter illustrates a traveling wave oscillation.

As was predicted, B and C differ in the following:

The maximum voltage in B is substantially more than the applied, while in C it does not exceed it.

The disturbance starts simultaneously throughout the winding in B and gradually progresses from line to neutral in C.

The first and second half of cycles are identical in C (3 + 33, 6 = 30, etc.) while in B the simultaneous distribution never occurs. This feature is not demonstrated on B where only the first half cycle is shown, as it would make the diagram unintelligible.

Thus it appears that the method used for the analysis of a transformer winding oscillation, being more general, is applicable to the analysis of a generator winding oscillation, while the reverse is not true.

F. D. Fielder and Edward Beck: The general agreement in the two papers dealing with surge voltages in rotating machines is gratifying. Mr. Boehne has laid more stress on one phase of the problem and we on another, namely the voltage distribution dur-

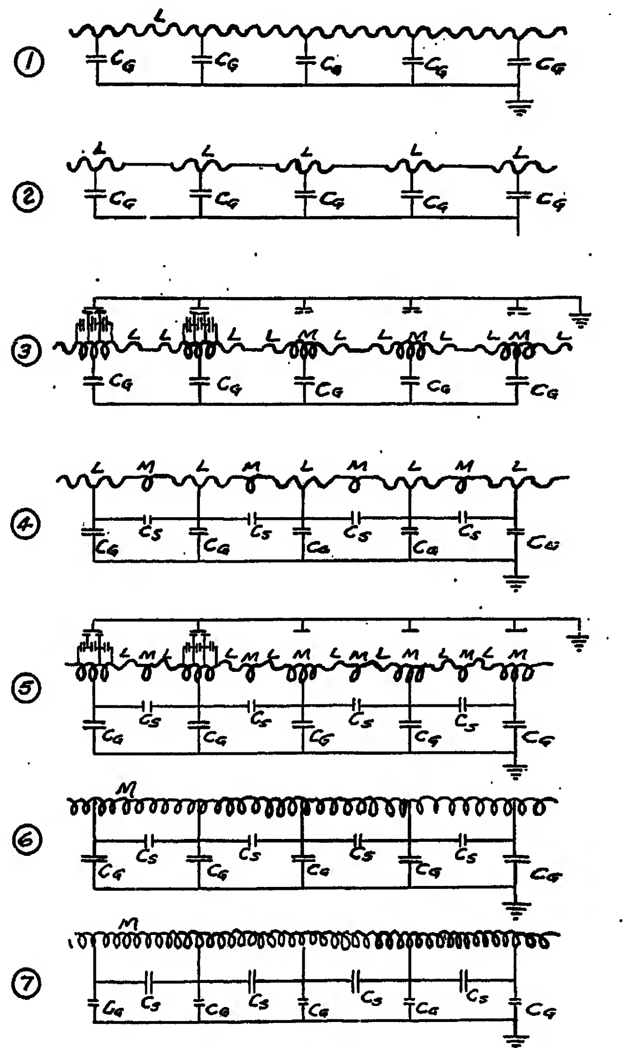

FIG. 12

ing the front of the incoming transient which we considered the most likely cause of trouble. Thus, the two papers together with the discussions present a rather comprehensive picture of the conditions as they are today.

Several methods of protection have been described, some of which we consider more efficient than others. In general, if the machine is directly connected to overhead lines the most efficacious way of influencing the distribution appears to be the use of distributed capacities or arresters. Of those methods which can be used without modifying the construction of the machine itself, we consider the use of a combination of inductance, capacity and arresters as illustrated in Fig. 14 of the paper the most efficient.

Other methods may sometimes be advisable considering the economics of the question. However, as pointed out in our paper arresters alone at the machine terminals may not prevent bad distribution; and the use of capacity only with an arrester, unless the capacity is large, may not exert sufficient influence on the wave front before the arrester commences to discharge to prevent poor distribution because, as pointed out in the appendix to our paper the rate of rise of voltage at the condenser terminals depends not only on its capacity and the effective surge impedance of the line but on the magnitude and steepness of the incoming surge. In the case of very high overvoltages the rate of rise of voltage up to arrester discharge may be high.

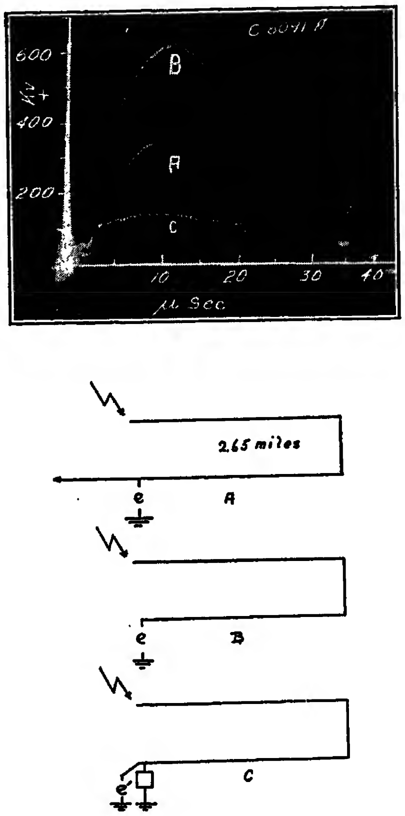

FIG. 13

Fig. 13 shown here is illustrative of Figs. 15, 16, and 17, of our paper. A surge from an impulse generator was applied to a transmission line and measured at a point 2.65 miles from its origin by a cathode ray oscillograph, the line extending beyond the oscillograph location so that there was no reflection at this point. Curve A is this traveling wave. The line was then terminated at the oscillograph location and the same impulse applied from the generator. The reflection of A produced a voltage B at this point. Next an autovalve arrester was connected from line to ground at the oscillograph location. On the application of the same impulse the voltage C appeared, this being the voltage across the arrester during discharge or in other words a volt-time characteristic. The flat top practically independent of discharge current, and smooth transition from the non-conducting to the conducting state are characteristics of this valve type arrester, further illustrated by the two volt-ampere characteristics of a section of such an arrester shown in Fig. 14.

Fig. 13 further shows that although the original wave reached its crest in a relatively long time, about 10 micro-seconds, the voltage rose to arrester discharge in about 1 micro-second which would give a distribution in a machine such as the one used in the tests described in our paper, between Figs. 4 and 6. The benefit of the addition of a wave sloping device is thus apparent.

E. W. Boehne: In the lightning protection of directly connected equipment the *fundamental consideration is the magnitude and duration of voltage stresses* of the various insulations in the machine. It follows, therefore, that the true measure of any protective scheme is its ability to reduce these insulation stresses. Now from a careful study of the phenomena presented in the paper it is apparent that the maximum stress which occurs between turns for any wave occurs at or near the line terminal and throughout the dissipation of this surge the stresses between turns at any point will never exceed this initial turn stress. This fact is independent of the condition of the neutral and is primarily the result of the change in wave form as the transient proceeds through the winding the first time.

This brings us to the consideration of the neutral resistor as an effective protective measure for open neutral machines as questioned by Mr. Palueff in the early part of his discussion. From the above paragraph it is evident that the only insulation which this neutral resistor is called upon to safeguard is the major insulation to ground. Any device which may be placed in the open neutral which will not allow the maximum voltage at the neutral under the most severe conditions to exceed the lightning arrester potential, has performed its function one hundred per cent efficiently. The most severe lightning condition in this respect is to have surges enter on all three phases simultaneously. The ideal resistor at the neutral under such conditions has been shown to be equal to surge impedance of all phases in parallel at the neutral. Now it is true that should surges enter on one phase or two phases only there will be a *negative* reflection at the neutral and a voltage oscillation will be set up in the machine. Here our fears are immediately relieved with the realization *that voltage oscillations in themselves are as harmless as thunder and need only be considered with respect to the stresses they may produce.* In the case of *negative reflections* at the neutral the potentials in the winding are obviously reduced, the maximum voltage to ground never being in excess of the lightning arrester voltage, the objective of neutral resistor.

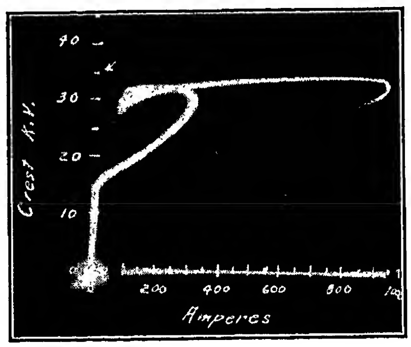

FIG. 14

In this respect the neutral resistor can have any resistance less than the above mentioned value and still be as effective in reducing the maximum voltages to ground.

The reader is referred to the last paragraph of the paper prior to the Summary and Discussion.

Fig. 12 of Mr. Palueff's discussion shows a very good summary of the transient investigations made upon generators and transformer windings, however, a great deal of flexibility accompanies such a classification. Mr. Palueff points out that the transformer theory of standing wave oscillations reduces to a simple traveling wave when the constants of the circuit are such that the various harmonics vibrate at a rate proportional to their order, that is, when the third harmonic vibrates 3 times as fast as the funda-

mental, the fifth 5 times as fast, etc. Such a case is more easily and clearly analyzed if the phenomena be considered as a traveling wave in the winding. On the other hand, in such circuits where the harmonics are found to vibrate at a slightly different rate than their natural order as mentioned above, does not mean that all the traveling wave properties of the phenomena are lost. Oscillograms taken on transformer winding have been found to exhibit traveling wave properties. Such a case is shown in Fig. 9 of Mr. Hodnette's paper, *Effect of Surges on Transformer Windings*," A. I. E. E. JOURNAL, Nov. 1929 and reproduced again as Fig. 2 in the Electrical Machinery Technical Report, Summer Convention, 1930. These oscillograms show clearly that the *fundamental oscillation* is caused by a traveling wave reflecting back and forth in the transformer winding as was found in the case of generator windings (compare with Fig. 1 of this paper).

Vertical Shaft 25,000-Kv-A., Synchronous Condensers

25-Cycle, 500-rev. per min., Outdoor Type Units for Toronto Leaside Transformer Station

BY H. A. RICKER,* J. R. DUNBAR,* and R. E. DAY*
Non-Member Member, A. I. E. E. Non-Member

Synopsis.—This paper is a description of the 25,000-kv-a., 13,200-volt, 25-cycle, 500-rev. per min., vertical-shaft, outdoor type, self-starting synchronous condensers installed in the Toronto-Leaside Transformer Station, of the Hydro-Electric Power Commission of Ontario. Some of the special problems encountered because of the vertical-shaft, outdoor type arrangement are discussed. In the appendix, the automatic starting and stopping sequence is given, with a comparison between the results obtained by using open circuit transition and the results to be expected by using closed circuit transition.

The following table of contents explains the plan of presentation followed:

* * * * *

I. Introduction

In November 1929 the first of the 25,000-kv-a. vertical shaft, outdoor type, synchronous condensers for the Toronto-Leaside Transformer Station of the Hydro Electric Power Commission of Ontario was placed in service. At the present time there are two condensers in service, and two more, which are now being manufactured, should be in service by the end of this year. The condensers are nominally rated at 25,000-kv-a., 13,200 volts, three-phase, 25-cycle, 500-rev. per min., 6-pole, zero per cent power factor leading, with maximum ratings of 30,000 kv-a. at 13,200 volts and 25,000 kv-a. at 14,500 volts. The specified capacity, under excited, is 12,500 kv-a. at 13,200 volts. The guaranteed temperature rise at normal rating is 60 deg. cent. by detectors in the armature winding and 75 deg. cent. by resistance in the field. These ratings were determined after extensive studies made by the Hydro-Electric Power Commission engineers, particulars of which are described in a companion paper.

These condensers are located at the receiving end of the Hydro-Electric Power Commission's 220-kv. transmission line from Paugan Falls to Leaside. It was decided that quick response excitation was necessary to insure proper operation of the condensers in this location. Accordingly, a laminated-frame, direct-connected exciter with a separate constant-voltage pilot exciter was used for each condenser. By this excitation arrangement, it was possible to obtain a calculated speed of response of the main exciter of the order of 800 volts per second.

Each unit includes the synchronous condenser, the laminated-frame main exciter, and the pilot exciter on one shaft. Before the units were ordered, an auxiliary synchronous motor was considered which would have been mounted on the same shaft as the condenser, and would have been of sufficient capacity to drive the condenser and to supply the losses of half a transmission line. It was decided, however, that the auxiliary motor was not necessary as the condenser could be brought up to speed from the Niagara System, and then the transmission line tested during the period in which the condenser was slowing down. It has since been found that the Hydro-Electric Power Commission (Gatineau) line may be connected to the Niagara System at full voltage, so line testing can be carried on without using a condenser. As mentioned elsewhere, a starting motor was not necessary.

II. Mechanical Design

Perhaps the first impression an engineer, accustomed to the arrangement of vertical shaft units, gets from the assembly of this condenser is that it is quite reversed to the usual. In fact it was a rather long study that produced the arrangement. One at a time, study after

*All of the Canadian Westinghouse Company, Limited, Hamilton, Canada.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

study, first the thrust bearing, then the large exciter with collector, next the pilot exciter and finally the speed relay went to the bottom. For this unit, it is doubtful if any other arrangement would have been more convenient.

III. Type of Condenser

Outdoor, Vertical-Shaft, Air-Cooled, Self-Starting

For some years things electric have been gradually moving to the out-of-doors. There seemed to be no insurmountable difficulty in putting these condensers also there. It only required that the units be covered with a suitable encasement and that they be arranged so that a miminum amount of exposure would be necessary in case of repairs.

One question in connection with the design has been repeatedly asked: "Why were they designed with vertical shafts?" Obviously a vertical unit could be more economically enclosed for outside location than could a horizontal unit. The removal of a rotor from the stator, or the arrangement of a unit so that the stator may be shifted clear of the rotor, usually presents a tedious problem with a large, high-speed, horizontal unit. Accordingly, a vertical unit should be preferred providing the head room could be kept within reason.

Open air machines with air filters were chosen. Fully enclosed machines were considered. With fully enclosed machines, water cooling of the ventilating gas would be required. Hydrogen could not be justified economically as the ventilating gas, since the peripheral speed of the condenser is not high enough to show a material reduction in losses with its use. Air would have to be used whether fully enclosed or open. Inasmuch as there would be no place in which to make use of the heat transferred from the air to the water, the water would have to be spray-pond cooled, which feature was undesirable. In addition, the cost of water coolers for the air was found to be more than double that of air filters.

The atmosphere in the vicinity of the station apparently would never be heavily laden with dust and smoke; accordingly the cost of maintaining air filters would not be high. Heated air could conveniently be circulated and used for the heating of the basement and tunnels.

In the event that it was found desirable to resort to water cooling at some time in the future, certain inexpensive alterations could be made to accommodate.

Self starting was desired. With the arrangement of forced lubrication to the thrust bearing as described in a subsequent paragraph, a special starting motor was not required. The starting kv-a. was specified as not to exceed 50 per cent of full-load kv-a.

IV. General Arrangement

The general arrangement of the unit on the foundation is well shown in Fig. 1, this figure being supplied by the Hydro-Electric Power Commission of Ontario.

On what we may term the ground elevation, the main stator stands on its support. On top of the stator, and supported on a stator frame extension, is mounted a comparatively light eight-armed girder type bracket for guide bearing support.

The thrust bearing is located at the ground elevation and is supported on a girder type bracket which, in turn, rests on the foundation. Beneath this thrust bearing bracket is located the main exciter, the stator of which is supported on another girder type bracket, while the pilot exciter and a speed relay are underslung from the main exciter bracket.

The whole main stator from ground elevation is encased in a housing suitably arranged for ventilation and for protection from the weather.

The unit, apart from the electrically active materials, is fabricated practically throughout of steel plate, bars, and sections. Only a few parts such as the upper guide bearing, some Kingsbury bearing parts, collector parts, and exciter spider are of cast construction.

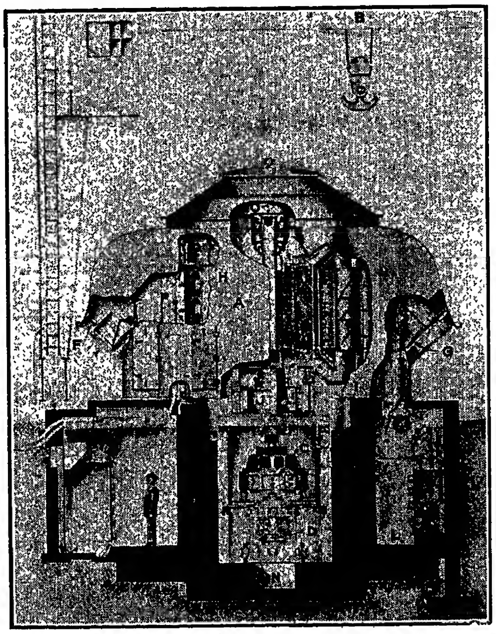

Fig. 1—General Arrangement of Unit on Foundations

A 25,000-Kv-a. condenser 500 revolutions per minute
B 80-Ton gantry crane
C 150-Kw. 125-volt main exciter
D 30-Kw. 250-volt pilot exciter
F Main incoming air damper
G Main outgoing air damper
H Recirculating air damper
I Damper for basement heating
J Spherical thrust bearing
K Upper guide bearing
L High-pressure oil pump for starting
N Truck for handling exciters
O Threaded hole for rotor lifting eye
P Air filters
Q Current transformers

The basement under the unit provides a convenient location, quite large enough for the necessary switching, for the oil pumps and storage, and for other incidental purposes.

V. Weights and Dimensions

The weight of the complete unit is approximately 210 ton. The stator frame of the main unit complete with iron and coils, weighs 84½ ton, the rotor of the main unit, completely assembled on the shaft, weighs 75 tons. The maximum weight required to be lifted by the crane at any one time is 85 ton. The weight of a

single pole with field coil is over 9½ ton, which weight is greater than a pole and coil of a Queenston 55,000-kv-a. generator. The field coil weighs nearly two ton itself. An armature coil, too, is longer, wider, and heavier than a similar coil from a 55,000-kv-a. generator.

The over-all height of the unit from the bottom of the speed relay to the top of the housing is 34 ft. The maximum width of the unit over the housing, exclusive of the ventilating extensions, is 19½ ft.

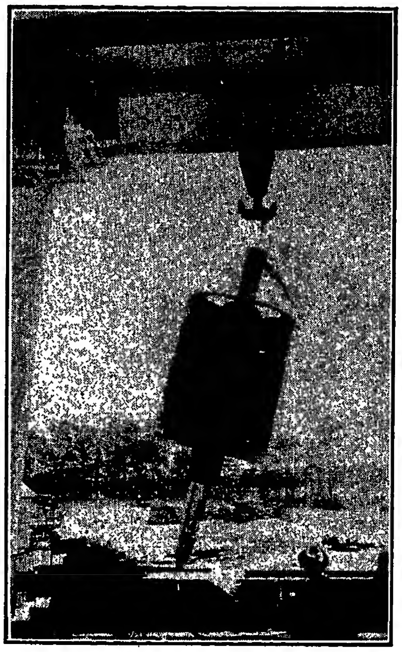

Fig. 2—Up-ending and Lifting of Rotor from Railroad Car

VI. Shipment and Installation

The arrangement of these units made necessary the installation of the thrust deck with bearing first. The

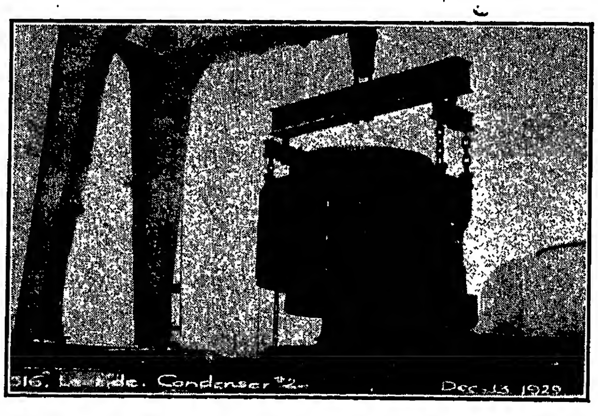

Fig. 3—Turning and Lifting Stator During Installation

rotor had then to be installed and lowered into the pit, after which the stator was put in place.

Before shipment, the rotor was completely wound. The stator winding was completed except for some of the end connections. Each, the rotor and the stator, made a heavy car load and each was turned horizontally for shipment. For the stator special clearances had to be secured from the railways as the coil ends overhung the width of the car. Fig. 2 shows fairly well the unloading and up-ending of the rotor. It may be noted that the regular lifting eye could not be used. A cable was threaded through the hollow shaft and a bushing with an easy radius for the cable inserted in the shaft end. Fig. 3 shows the stator lifted with a beam after the turning had been completed.

VII. Detail Description—Stator

A detail cross-section of the unit is shown in Fig. 4.

The design of the active material of the stator and rotor presented few new problems.

In order to keep the peripheral speed at a reasonable value, the condenser had to be built with a core width of 80 in. On account of the low temperature guarantee and considering the great depth of the armature punchings of a six-pole machine, the core had to be divided into unusually small sections. These sections are separated from each other by I-beam spacers. In

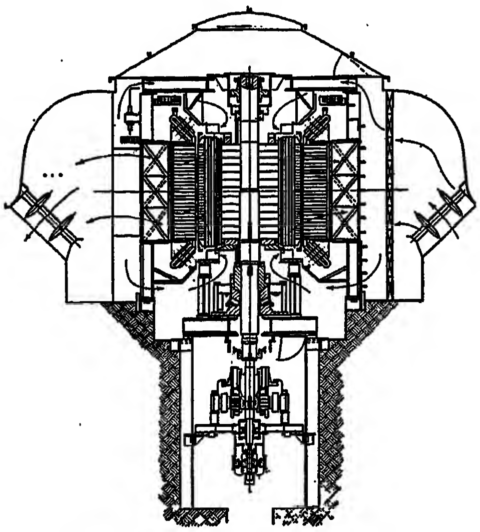

Fig. 4—Cross-Section of Unit

addition to these regular air ducts provided for ventilating purposes, a one-inch duct has been provided in the center for the purpose of facilitating the removal of armature coils.

The armature coils are insulated with micarta folium, which will stand an operating temperature of 150 deg. cent. without injury. Each coil is made up of four turns subdivided into eight strands each, with some of the strands mica-taped in order to insulate them from the adjacent strands and so to reduce eddy-current losses. To reduce still further additional losses, the winding has also been transposed once between coils.

The stator frame is constructed of steel plate and bars, amply braced. A large ventilating hole is provided in the outer frame plate for the outlet of hot air. Two smaller openings are provided for the mounting of the customer's re-circulating dampers. Two heavy plates, one on each side of the frame, are welded in for the mounting of trunions for use in lifting and turning the stator. The silicon steel laminations are assembled on round rods rather than in slotted dovetails. The coils are formed in the usual way, with sufficient clearance

between coils on the diamond ends to pass insulated bolts for bracing to the triangular shaped brackets, in turn bolted to the stator end plates.

This style of coil bracing is without a doubt one of the best, if not the very best, for coils of wide throw. It has some disadvantages, such as requiring a little more copper on the coil ends, and it is expensive. However, to offset the objections, it is, when properly applied, a most rigid form of bracing and little trouble is ever experienced with it.

VIII. Detail Description—Rotor

The field coils are made up of three different sizes of straps of which the widest has a width of 4.5 in. The insulation between turns consists of two layers of asbestos with one layer of mica sandwiched between. This was desirable on account of the high pressure between turns, due to the centrifugal force. The coils are insulated from the poles with mica, which insulation will stand a temperature of 150 deg. cent. continuously.

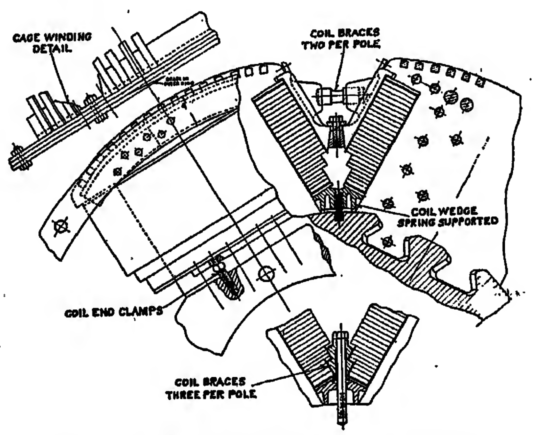

Fig. 5—Some Details of Rotor Design

The rotor spider is of plate steel construction dovetailed for the poles. Each pole is provided with two dovetails. Each dovetail is keyed on each side with a single taper key. The dovetail slots in the rotor are skewed sufficiently to allow for the key taper. With this method of keying, the designer need not provide a radially split-pole body to be assured of good dovetail contact on all four sides as is often done when two keys are used on one side only of each dovetail.

Some details of design may be seen by referring to Fig. 5.

Located between adjacent coils, and next to the spider is a metal wedge to present a flat rest for and to support the coil insulation. Under this wedge, and inserted in drilled holes in the spider, is a series of coil springs that press against the metal wedge in order to insure tight insulation even after some shrinkage in service.

One of the points that required the most careful consideration was the design of suitable braces between coils to counteract the tangential forces of the coil sides. The space was limited and the ventilation between poles could not be blocked. These braces had to be held in place by the pole tips. This required several inches of nickel steel laminations in the pole.

The starting squirrel-cage winding required special attention to satisfy the current carrying requirements and the centrifugal force. The bars were brazed to angles of copper and these angles, in turn, bolted to a laminated ring consisting of hard drawn copper bars bent cold and brazed. Each ring is of three thicknesses of copper, the brazes of different sections of the ring being located at 120 deg. so that two-thirds of the ring cross section consists of good hard copper, the tensile properties of which are good.

The ventilating fan located on the top of the rotor is formed of comparatively thin plate while the fan located at the bottom is of very heavy construction. This fan forms also the brake ring used in stopping the unit. It also forms the support on which the rotor rests when the thrust bearing is opened for inspection, or is removed. Inasmuch as this ring has to form a blower, it had to be designed for that purpose; it had to have sufficient capacity for heat to give a limited amount of expansion when braking; and it had to be strong enough to support the rotor weight at the four brake points and to resist the torque due to friction.

IX. Detail Descriptions—Brackets, Bearings, and Housing

Upper Bracket. The upper bearing bracket, or guide bearing support, is arranged with a demountable center, rectangular in shape, only large enough that the crane block may pass through the hole. This demountable center may be removed through the outer encasement through a round hole of approximately the same size. This arrangement permits the attachment of the crane to the shaft without the exposure of the whole top surface of the unit as would be the case if the entire top bracket had to be removed.

Lubrication and cooling of this top guide bearing is accomplished by forced oil feed from a circulating pump. Only a small portion of the oil is allowed to drain down through the rotor. The arrangement is a little unusual inasmuch as the feed is at the bottom of the bearing and the main overflow is at its top.

On the top of this guide bearing is located a small annular oil pot that fills automatically with overflow oil from the bearing. This container forms a reservoir for automatic feed back to the bearing during the shutdown period and as an emergency protection in case the lubricating system should fail.

Thrust Bracket. The thrust bearing bracket is naturally of very stiff construction. It consists primarily of heavy H-beam girders with plates welded top and bottom. Mounting is provided on the top plate for the air brake pedestals.

The oil reservoir is, in this case, mounted on the thrust-bearing base plate for convenience of insulating.

It is made square, with demountable cover and side plates.

Thrust Bearing. An enlarged detail cross-section of the thrust bearing is illustrated in Fig. 6.

This bearing is of the Kingsbury tilting-shoe type. The shoes and runner differ from the ordinary in that their actual bearing faces are spherical, so that the bearing forms not only the thrust bearing but also the lower guide bearing of the main unit. This bearing seems to be particularly applicable to these units. The fact that it occupies a minimum of space and is extremely easy to dismantle in a limited and difficult position are perhaps the principal points in its favor. It is self-alining, self-contained, and easily lubricated.

The heat generated in the oil film of this bearing has to be dissipated by external means. In the preliminary study air coolers for the oil, located in the passage of the incoming air, were considered. The cost was found to be excessive, so water cooling was resorted to.

Owing to the fact that the thrust bearing space is limited, there was not room for the ordinary arrange-

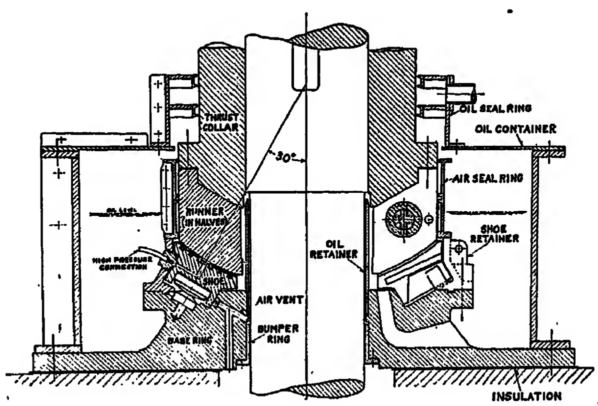

Fig. 6—Cross-Section of Kingsbury Spherical Bearing

ment of cooling coils in the oil pot. Thus, an external system of oil circulation to the bearing is employed. The oil drained from the bearing is cooled with water from the customer's spray pond, circulated in suitable coolers.

In order to have easy starting, a high-pressure pump is arranged to force oil through a lead to the center of each Kingsbury shoe surface. This is the first application of its kind made to a Kingsbury bearing. As in similar applications with horizontal journal bearings the starting torque required is reduced considerably.

Exciter Bearing. The exciter guide bearing is self-lubricated by centrifugal force and is self-cooled, radiating fins being welded to the housing. It is located at a point too low to permit the draining of oil from it, back into the main lubricating system.

Speed Relay. The speed relay located on the bottom end of the exciter shaft operates centrifugally. It has three functions to perform, one of which is to cause the machine to be cut out of service in case of a dangerous overspeed. It also permits the application of field current to the condenser during the starting cycle and causes the application of the air brakes during the stopping cycle. These latter two functions are referred to again.

Housing. The contract for the condenser included the metal encasement necessary to the protection of the unit from the weather and for ventilation. The Hydro-Electric Power Commission designed and supplied the housing extensions with dampers which are located on the air intake and outlet sides.

The outer housing is made large enough for one to walk around the condenser frame within the cold air duct. Entrance is provided through a full-sized door in the vertical wall.

The main portion of the cover of the encasement is conical in shape and is provided with a foot rail around its circumference. The extreme top cover is spherical. Both portions of the cover are lagged with felt to prevent possible condensation. This lagging hardly seems necessary, for the air within does not circulate, and the volume is so small it could not contain enough moisture to do harm. Inside the cover is a floor supported by the bearing bracket. This floor is provided with a manhole through which one may crawl after climbing up the ladder located on the condenser frame side. Another ladder is provided on the outside of the casing so that one may enter the top of the machine either from the outside or from the inside of the casing. To be able to enter this portion of the machine is quite important especially during the period of the balancing of the rotor.

Inasmuch as the customer proposed to resort to carbon dioxide for fire extinguishing, the encasement had to be made practically gas tight. All joints not actually welded are provided with felt and canvas gaskets.

To complete the enclosure a plate covering, with manhole, is provided on the underneath side of the thrust bearing deck.

X. Maintenance

In order to remove the two exciters from under the main unit the Hydro-Electric Power Commission have provided a light truck on a track below the exciter level. This truck may be moved along the track under the exciter supporting bracket. Jacks are provided on the truck to lift the two exciters. The truck is illustrated in Fig. 1. After the electrical leads and mechanical attachments are disconnected, the truck with exciter support bracket and exciters may be moved along the track out of the way. The exciter shafts and bracket are arranged in such a manner that the weight of the armatures is carried by the bracket when the shaft flange is disconnected.

The condenser rotor and thrust deck may now be lowered into the pit thus cleared, a ring key being first inserted around the shaft under the thrust deck in order that the thrust deck may be lifted and lowered with the

rotor. Upon removal of the upper guide bearing and its supporting housing the crane hook may be attached to a suitable eye bolt screwed into the shaft. The rotor and thrust deck are then lifted slightly so that bridge plates under the arms of the thrust deck may be slid back out of the way and the main rotor lowered into the pit under the stator, the thrust deck arms following down slots provided in the foundation.

With the rotor in this position cleaning and all ordinary repairs may be done to the rotor and stator windings.

XI. Ventilation

Normally the air for cooling the units (see Fig. 4) enters at one side through the housing extension. Here it is filtered before it enters the cold air housing. From this duct the air is distributed to the top and to the bottom of the machine, where the previously described fans force it between the poles, along the air-gap and through the ventilating ducts in the laminations. From the back of the laminations the air is carried around inside the frame, which forms the hot air duct, where it normally exhausts into the atmosphere through the opposite housing extension.

To describe fully the heating and recirculation system designed and installed by the Hydro-Electric Power Commission would take considerable space and the details of that description can well be left to the designers who are more familiar with it. For the purpose of this article, it will be sufficient to state that a fully automatic scheme is devised so that hot air may be recirculated in the rear of the air filters to prevent them from freezing over in bad weather, and to regulate the flow of cold air to the machine. Arrangement is also made that the temperature of the basement under the units will be regulated by a flow of air through dampers inserted in the basement ceiling. Any degree of heating may be acquired. The arrangement is shown in some detail in Fig. 1.

XII. Bearing Protection

Every designer of electrical generators and motors will state that shaft currents are the greatest enemy that bearings have. It is good practise, especially on important installations, to guard in the design, against the possibility of these currents flowing, whether or not they are anticipated. Accordingly all bearings on these units are insulated. In fact the complete rotor is insulated from the stator so that a simple test may be applied at any time to determine if the insulation is intact. Tests made after installation indicate that this precaution was not necessary on this installation as the potential taken from end to end of shaft was found to be very small, certainly not sufficient to break down an oil film.

Each bearing is provided with a thermometer for bearing temperature indication, also with a hand reset thermostat whose contacts will close and start in operation the stopping cycle in case the bearing temperature exceeds the temperature for which the thermostat is set.

Each machine has two oil circulating pumps so arranged that if one pump should fail in operation, the other will automatically start. In addition, if the oil pressure fails, a relay will operate causing a shutdown.

XIII. Fire Protection

At both top and bottom of the armature is installed a sprinkler pipe for water. The sprinkler pipe is of copper to prevent the possibility of corrosion. To make these pipes of copper does not add materially to the cost but it would appear to be an unnecessary precaution.

The Hydro-Electric Power Commission have installed a complete carbon dioxide flooding equipment which, no doubt, would be used in preference to the objectionable water system. The water system would be brought into play only as a last resort.

XIV. Electrical Protection

Electrically the machine is protected by the commonly described split-phase balanced relay system. This system, since the stator is in three parallels, required the installation of 18 current transformers on the legs of the different phase parallels. These 18 transformers are mounted on the top frame extension and are equally spaced around the circumference. The mounting of these transformers is illustrated in Fig. 4.

A relay arrangement will actuate and cut the machine out of service if either the field or armature is overloaded for a dangerous period. Another arrangement will cut the machine out of service if the voltage drops below a predetermined value on the armature, or if the condenser should lose its field.

Thermocouples are located in the armature slots so that the temperature of operation may be recorded.

Realizing that a partially shorted field, due to unbalanced magnetic pull, might cause serious damage to the unit, not only was special insulation used on the field coils, but a ground detector for the field was also installed. This detector may or may not, at the customer's wish, be arranged to cut the unit out of service.

XV. Ground Detector

The ground detector circuit is as shown on Fig. 7. A voltage of 110 a-c. is applied through the coil of a relay to the mid-point of two resistors connected across the field circuit. One side of this a-c. circuit is grounded so that a ground anywhere on the field circuit will complete the circuit and cause operation of the relay. The relay has a ½ ampere setting and the equipment has been found to be very sensitive. In case the apparatus indicates a ground, the same may be removed before a second one occurs to produce the objectionable short circuit.

Owing to the bearings being insulated, it was necessary to ground the rotor shaft through a brush in order

that the ground detector circuit might be effectively completed in case of a ground on the rotor winding.

This ground detector scheme does not increase the voltage between any part of the field circuit and ground, and it protects the exciter armature as well as the condenser field. It has the same sensitivity regardless of the voltage across the main exciter armature and field circuit.

XVI. Calculated Electrical Characteristics

Fig. 9 shows the calculated no-load and full-load zero per cent power-factor saturation curves, also the short-

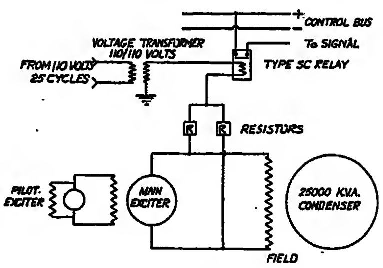

Fig. 7—Field Ground Detector Connections

circuit current and the V-curve at 13,200 volts. The transient reactance of the condenser is calculated to be approximately 32 per cent and the short-circuit ratio is approximately 0.7.

The excitation required at 30,000 kv-a. 13,200 volts,

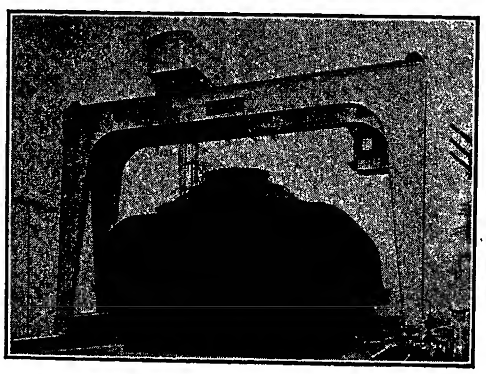

Fig. 8—General View of Location after Installation of No. 1 Condenser

zero per cent power factor leading, is approximately 100 kw. and the guaranteed total loss at 25,000 kv-a., 13,200 volts, zero per cent power factor leading is 510 kw.

Up to the time of preparation of this paper, tests had not been made, but casual readings taken during operation check the calculated values reasonably well.

XVII. Starting and Stopping Procedure

The starting and stopping of these machines is entirely automatic. When the starting button is pressed, relays take control, and if everything is normal, the complete sequence of operations progresses until the condenser is synchronized under regulator control and is carrying its share of the load. When the stopping button is pressed, or a protective relay operates, the condenser is automatically disconnected and brought to rest by a combination of dynamic braking and air brakes. This is amplified slightly in the Appendix.

By the use of the customary three-breaker method of reduced voltage starting, with open circuit transition from starting to running voltage, it was found possible to keep the inrush during the starting period down to a

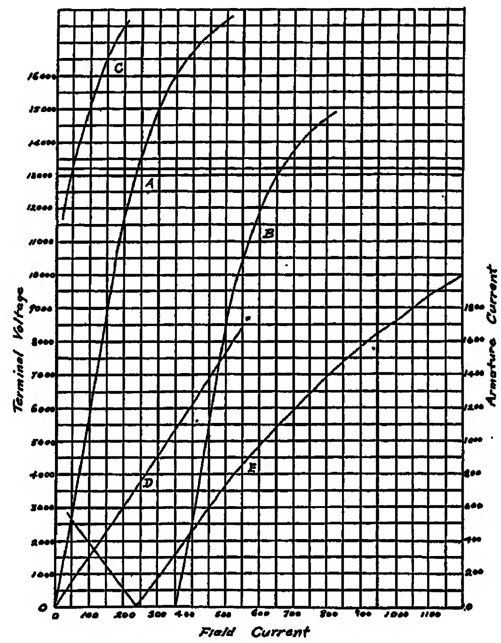

Fig. 9—Calculated Saturation Curves of the 25,000-Kv-a. Condensers

A. No-load saturation
B. 1095 Amperes, 0% P. F. leading saturation
C. 548 Amperes, % P. F. lagging saturation
D. Short-circuit saturation
E. V-curve, 13,200 volts

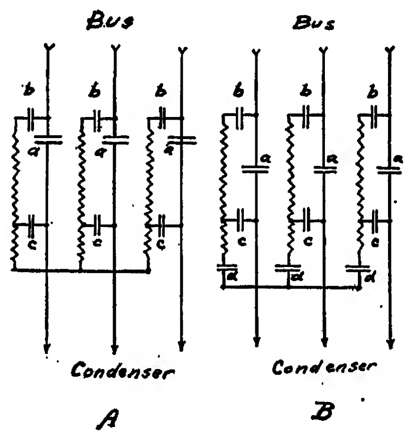

Fig. 10—Open- and Closed-Circuit Methods of Starting

A. Open-circuit transition
B. Closed-circuit transition

reasonable value, so that there was no undue disturbance to the bus voltage. Closed circuit transition was considered but it was discarded as being of no material assistance, and it would introduce an extra breaker, since the Commission did not wish the auto-transformer to be energized all the time. Fig. 10 shows diagrammatically the connections for the open-circuit method

that was used, and for the closed-circuit transition method that was considered. The sequences of breaker operation are as follows:

For the open-circuit method:

To start: (1) Close breakers *c* and *b*

To change to running position: (2) Open breakers *b* and *c*

(3) Close breaker *a*

For the closed-circuit method:

To start: (1) Close breakers *c*, *d*, and *b*

To change to running position: (2) Open breaker *d*

(3) Close breaker *a*

(4) Open breakers *b* and *c*.

The current that would flow at the instant of starting is the same for either method, if the same transformer

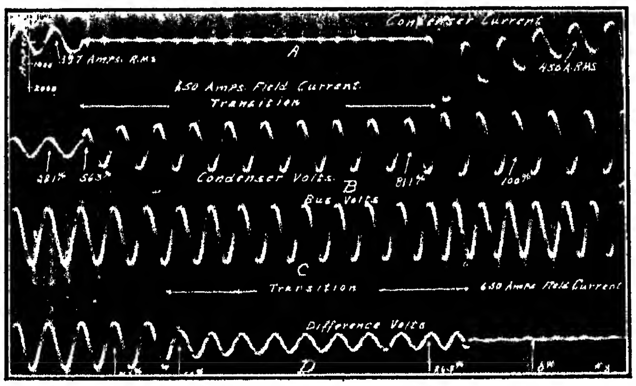

Fig. 11—Oscillograms of Transition Period; Field Current 650 Amperes

A. Line current
B. Condenser terminal voltage
C. Bus voltage
D. Difference between condenser terminal voltage and bus voltage

tap is used. Also with the equipment supplied for this installation, the current rush at the moment of transition is practically the same, if the time of transition is the same. If closed circuit transition is used, and the voltage of the condenser is adjusted to be equal to line voltage, with the condenser operating in synchronism through the auto-transformer, the inrush is increased. This is discussed in detail in the Appendix.

XVIII. Operation

The only tests that had been made, previous to the writing of this paper, were starting tests, to determine the best auto-transformer tap and the best value of field current to use. Fig. 11 is a print of oscillograms showing:

A. Line current
B. Condenser terminal voltage
C. Bus voltage
D. The difference between the condenser terminal voltage and the bus voltage.

The field current for these oscillograms was 650 amperes, which, as reference to the calculated saturation curves Fig. 9 will show, is approximately the full load field current for normal voltage. The auto-transformer was connected for a turn ratio of 26.2 per cent. The starting tests seem to indicate that this gave the least disturbance on transition, with a low value of starting kv-a.

It is noteworthy that with this particular installation the condenser invariably reached synchronous speed on the low voltage applied by the auto-transformer and before field current was impressed.

As has already been mentioned, casual readings taken from time to time during operation seem to be close to the calculated figures. It is shown in the Appendix that the oscillograms reproduced in Fig. 11 check calculated figures very closely.

Appendix

The operation of this station being completely automatic it may be of interest to give a very brief outline of the starting and stopping steps as they take place. Starting and stopping and protection are controlled by a number of relays.

Normal Starting. When the starting button is pushed a master relay closes, provided all conditions are normal. This relay remains closed only providing operation after operation takes place in regular and proper sequence. For instance, it will not close if the phase rotation is reversed or if the line voltage is too low, if the air brakes have been left on by hand control, or if any other operation has not been properly performed.

The master relay closing causes, first of all, the high-pressure pump connected to the Kingsbury bearing shoes, as well as one of the oil circulating pumps, to start. When the oil circulation has been built up to the proper value and after a lapse of time, in which a film of oil is being forced to the Kingsbury shoes, a contact making gage causes, provided other conditions are normal, the starting and magnetizing breakers to be closed and reduced voltage to be applied to the condenser, at which time the field will begin to rotate. When the speed of rotation has reached a required value, field is built up on the condenser and when the field current reaches a predetermined value the transition occurs, that is, the starting breakers open and the running breaker closes, at which time the condenser is automatically put under the control of the voltage regulator, and it takes its share of the load. At this time the high-pressure pump stops.

Normal Stopping. Pushing the stop button, or the operation of a protective relay, causes the opening of the same master relay used in starting. When this relay opens, the condenser is disconnected, the oil circulating pump stops immediately, and the condenser field breaker opens. Upon the opening of the condenser field circuit, the breaker controlling the dynamic brakes, closes the main exciter armature circuit through a re-

sistor and as the main exciter field is maintained a load is imposed on the exciter, quickly reducing the speed of the whole unit.

When the speed has been reduced by this means to one-half of full rev. per min., a contact on the speed relay closes and the air brakes are applied. The application of the air brakes removes the dynamic braking.

Test Values. The values of current and of voltage, as read from the oscillograms shown in Fig. 11, are as follows:

Condenser terminal voltage (per cent of bus voltage)		
Before transition		28%
After starting breaker is opened		56%
Before the running breaker was closed		81%
Difference between condenser terminal voltage and bus voltage (per cent of bus voltage)		
Before transition		72%
After starting breaker is opened		50%
Before the running breaker was closed		26%
Line current (per cent values are in per cent of condenser rated current)		
Before transition	397 amperes, r. m. s	36%
After transition		
Maximum unsymmetrical	2750 amperes peak	178%
A-c. component		
Initial value	940 amperes r. m. s.	86%
At first peak	850 amperes r. m. s.	77%
D-c. component		
Initial value	1840 amperes peak	116%
At first peak	1600 amperes peak	101%

Open Circuit Transition. The current which flows momentarily when the condenser is connected to the bus at the conclusion of the transition period is proportional to the difference between the condenser terminal voltage and the bus voltage, if the d-c. component and components due to subtransient reactances are neglected. This difference is vectorial and depends on the magnitude and direction of the vector representing condenser terminal voltage. Fig. 12A shows the vector diagram of voltage corresponding to the oscillogram shown in Fig. 11. This indicates that the condenser terminal voltage lags behind the bus voltage by approximately 12 deg. The value of this angle of lag depends on the losses and on the fly wheel effect of the rotor. It would therefore be expected that with a higher value of field current this angle of lag would be greater since the losses are higher. This is borne out by Fig. 12B which shows the corresponding vector diagram obtained from other oscillograms for 750 amperes field current, showing an angle of lag of approximately 12½ deg.

The voltage which appears at the condenser terminals immediately after the starting breakers are opened is equal to the internal voltage in the condenser before the breakers were opened. With 650 amperes field current and with the condenser connected to the 26.2 per cent tap the line current was 397 amperes. This gives approximately 1500 amperes in the condenser. From the calculated saturation curves, Fig. 9, and from the calculated characteristics of the condenser, the current that should flow for 650 amperes field current with 28 per cent terminal voltage would be approximately 1700 amperes. This is a reasonably good check considering that the curves used are calculated, and the test result is taken from an oscillogram. Using the 1500-ampere value of current and the calculated machine characteristics, the internal voltage would be approximately 58 per cent of rated voltage. This checks well with the oscillogram value of 56 per cent. During the transition period the field voltage is higher than the $I\,R$ drop corresponding to the field current flowing, due to the inductive kick which reduces the field current when the starting breaker is opened, and therefore the field current tends to increase and the terminal voltage tends to "creep." From the oscillo-

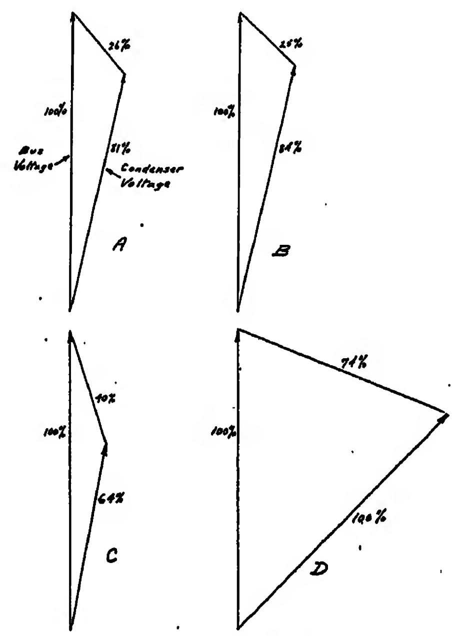

FIG. 12—VOLTAGE VECTOR DIAGRAMS AT INSTANT OF CLOSING RUNNING BREAKER

A. Open-circuit transition—650 amperes field current
B. Open-circuit transition—750 amperes field current
C. Open-circuit transition—300 amperes field current
D. Closed-circuit transition

grams taken, when the running breaker was closed the terminal voltage had increased to 144 per cent of the value immediately after the starting breaker was opened. This increase is reasonable considering the design of the excitation system.

It is possible to calculate the vector difference between the condenser terminal voltage and the bus voltage for other values of field current and of starting voltage by following the above procedure. The magnitude of the condenser terminal voltage is equal to the internal voltage before the starting breaker was opened, which can be readily calculated, plus the "creep." The "creep" may be interpolated from figures for other values of field current, or may be calculated from the condenser and exciter characteristics. The angle of

lag may be interpolated from test figures, or it may be calculated from the losses, the flywheel effect of the rotor, and the time of transition.

Fig. 12c shows the vector diagram corresponding to 300 amperes field current with the condenser terminal voltage vector interpolated from the oscillogram results. From this it will be seen that the difference in voltage is 40 per cent, which is much higher than for 650 or 750 amperes field current.

Current Values. The initial value of the a-c. component of current which flows immediately after the running breaker is closed is equal to this difference in voltage divided by the transient reactance of the machine. Using the figure of 26 per cent for the difference in voltage and the calculated transient reactance of 32 per cent, the initial value of the a-c. component is found to be 81.3 per cent. This is a very close check with the oscillogram value of 86 per cent. In fact, these oscillograms justify this method of computing the a-c. component of current after the running breaker is closed. Of course an allowance must be made for the d-c. component in determining the maximum unsymmetrical value of current which may flow. In this case the maximum unsymmetrical value is practically double the initial value of the a-c. component.

By means of this method the a-c. component of the current on transition for 300 amperes field current would be approximately 125 per cent. This is very much higher than the value corresponding to 650 amperes field current, and it is thus seen that the high value of field current gives better transition conditions. The oscillograms and the analysis show very little difference between 650 and 750 amperes but the tests seem to indicate less disturbance for 650 amperes.

It must be mentioned, however, that the second condenser was operating on the bus, under regulator control, during these tests. This is the normal operating condition for this installation. With this condition, the automatic regulator on the second condenser would hold the bus voltage constant, even though the leading current drawn by the incoming condenser tends to raise it. If there were no other condenser on the line, it is probable that a lower value of field current would give better results, since the higher value of excitation would tend to raise the bus voltage while on the starting tap, so that the difference between bus voltage and machine voltage would not be much diminished by using very high values of field current.

Closed-Circuit Transition. With the closed circuit method of transition, the series winding of the auto-transformer is left in circuit between the bus and the condenser, so that current will flow depending on the excitation characteristics of the transformer and on the voltage across the transformer. Fig. 13 shows the excitation characteristics of the auto-transformers used with the Leaside condensers when connected on the middle tap (28.4 per cent). When the transformers are connected for the 28.4 per cent tap there are 90 per cent of the turns in the series winding as when they are connected for 26.2 per cent tap. Therefore the values of current and voltage as read from Fig. 13 must be corrected by this factor to give the values for the 26.2 per cent tap.

As an initial approximation let us assume that the voltage across the transformer is equal to the difference in voltage between the condenser terminal voltage and the bus voltage in the open circuit method. For 650 amperes field current this voltage is 26 per cent and the corresponding exciting current for the auto-transformer is 0.05 per cent of the condenser full-load current. This current is so small that it can have practically no effect on the starting characteristics of the condenser and therefore the current inrush for the closed circuit

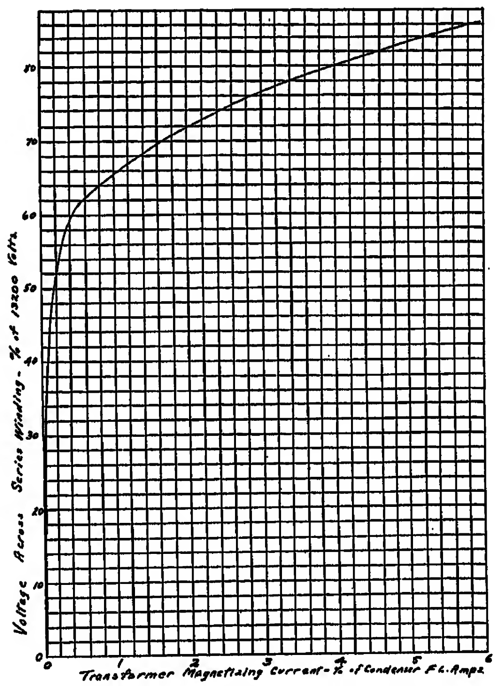

FIG. 13—EXCITING CURRENT OF STARTING AUTO-TRANSFORMERS FOR 27.4 PER CENT TAP

method with high speed timing of the breakers would not change the starting characteristics materially.

If a pause is made between the time of opening the neutral breaker and of closing the shunt breaker, sufficient time may elapse to allow the machine to build up to normal voltage and to reach a condition of constant phase angle displacement behind the bus voltage. On the assumption that the machine voltage is thus adjusted to equal the bus voltage, the phase angle between the condenser terminal voltage and the bus voltage will be determined by the voltage across the series winding of the transformers. If we assume that one per cent of machine rated current is required to supply its losses at no-load and to keep it in synchronism we find that the voltage across the series winding of the

auto transformers must be 74 per cent in order to pass this current, neglecting power factor. The vector diagram for this condition is shown in Fig. 12D. Again the a-c. component of current after transition is equal to the difference between the condenser terminal voltage and the bus voltage divided by the transient reactance, that is 231 per cent. This is considerably higher than the current obtained by the open-circuit method of starting.

Conclusion

The above theoretical considerations show that for the Leaside condensers the optimum condition for starting is with a field current of the order of full-load field current using the open circuit method of transition. Tests confirm that the field current should be approximately equal to the value corresponding to rated full load on the condenser, and show that the best results are obtained with the 26.2 per cent starting tap on auto-transformer.

Discussion

F. H. Chandler: This paper is an important addition to the very few we have had on the subject of the designs of large synchronous condensers, especially as these machines have a number of new features and are unique in being the first and only outdoor condensers of the vertical type in operation.

There are one or two features of this installation mentioned in the paper which I believe may be enlarged upon with interest to the plant engineer.

Ventilation

The past practise of providing ventilating air control on electrical machines of the open or straight through type has been by means of manual controlled dampers or no dampers at all. The application of CO_2 gas to automatically controlled machines for fire protection, and the departure from indoor to outdoor rotating machines demand electrical damper controls which are as essential to the machine as its relay protection.

The main ventilating dampers of the Leaside condensers are automatic in operation, stream line in design for quietness of air flow and are capable of handling 50,000 cu. ft. of air per minute which is the machine requirement. They close automatically in sequence when shutting down the machine and open to the full open position when the machine is started. These dampers are operated by d-c. valve type motors rated at 12 lb. ft. at 230 volts. A shock absorber of spring construction is used in this mechanism to make certain that these dampers close tightly, these springs having a deflection of 1 in. in compression at 1500 lb. Provision is also made for partial opening or closing of the dampers to suit weather conditions by push-button control. Means are also provided to supply heat to the windings from the basement during shutdown periods in the winter months to prevent condensation on the windings.

Bearing in mind the wide variation in temperature during summer and winter months with resultant contraction and expansion of copper in the coils, the Commission has endeavored by means of thermostatically controlled dampers to minimize this variation. A minimum temperature of 85 deg. fahr. has been arbitrarily set as the outgoing air temperature of the machine which is satisfactory for basement heating. The principle of the control is such that the required quantity of discharge air at 85 deg. fahr. is automatically mixed with incoming air at temperatures ranging from 30 deg. fahr. below zero and up, to maintain the discharge air at 85 deg. fahr. This temperature will, of course, exceed 85 deg. fahr. during extreme summer heat. The recirculation dampers have a maximum by-pass rating of 25,000 cu. ft. per minute.

Butterfly dampers are used for re-circulation with gearing arrangement such that without the timing relay the damper will operate from full open to close in 10 minutes. To allow the ventilating air time to adjust itself to the new condition and to prevent hunting of this damper, the Commission has developed a special centrifugal contactor operating on the float principle in oil which allows 30 sec. operation of the damper and five min. time interval before the next operation. If the thermostats have opened in the meantime the dampers remain in that position until load change or outside temperature change again starts the operation. With this arrangement 90 min. is taken for full one-way operation of the damper.

When an internal machine failure occurs causing operation of the differential relays, the automatic features are such that the main dampers close, the re-circulating damper opens, and CO_2 gas is discharged inside the case on the incoming air side of the machine. The damper used for heating the basement is automatically tripped by the gas when discharged, confining the gas in the machine case.

Totally enclosed machines were considered, but the cost of cooling ponds, pumps, etc., for the air coolers on a transformer station site was considerably in excess of the arrangement provided. Reasons against the use of hydrogen cooling have been mentioned in the authors' paper. At the time of the purchase of these machines, the Commission was not convinced that a satisfactory sealed casing with vertical bearing glands had been developed and that the machines would be immune from the hazard of explosion. Water cooling would also be required for this ventilating medium.

Machine Foundations

Vertical machine foundations where massive power house substructure is not available necessitated in the case of the Leaside condensers an exhaustive study to arrive at the proportions used. All articles in leading periodicals were referred to with the result that little authentic data could be produced.

Analysis of the sub soil taken from test holes drilled at the extreme corners of the foundations showed an average of 80 per cent clay, 2.9 per cent shale and 16 per cent sand which can be considered for rotating machinery as being capable of safe loading up to 2000 lb.

The only formula for computing the foundation mass which appeared to have merit, and which was not a proportion based on past experience, was received from one of the large turbine manufacturers. This formula is as follows,—Weight of foundation equals weight of machine times the cube root of the speed in hundreds. In the case of the Leaside condensers, this works out that the weight of the foundation is 1.71 times the weight of the machine. Our final design calculation shows this ratio to be 1.76 to 1. Soil pressure has been calculated at 1510 lb. per sq. ft.

A very accurate balance of the machine has been obtained, its high speed, heavy pole pieces and small rotor diameter demanding a running balance in the field. It has been noted that a 2 lb. weight one side of the rotor 20 in. from shaft center will throw the machine considerably out of balance.

Seven months' operation under the most adverse weather conditions have proven that the designs adopted have been exceedingly practical.

G. D. Floyd: The synchronous condensers described in the above paper were purchased primarily for power factor correction at the Toronto-Leaside Station. The proper regulation of the 220-kv. line from Paugan Falls to Leaside requires that the load at the receiving end have a power factor of approximately unity and as the load power factor might be 90 per cent lagging or less, synchronous condensers of approximately 100,000 kv-a. capacity were required to meet this condition.

The benefits to be derived from quick response excitation were

appreciated and excitation of this type was specified although no definite values as to the amount of response were laid down, this question being left to the discretion of the manufacturer.

A number of tests was made recently to determine the quickness of response of these condensers under various conditions.

Fig. 1 shows the response of two condensers to a simultaneous

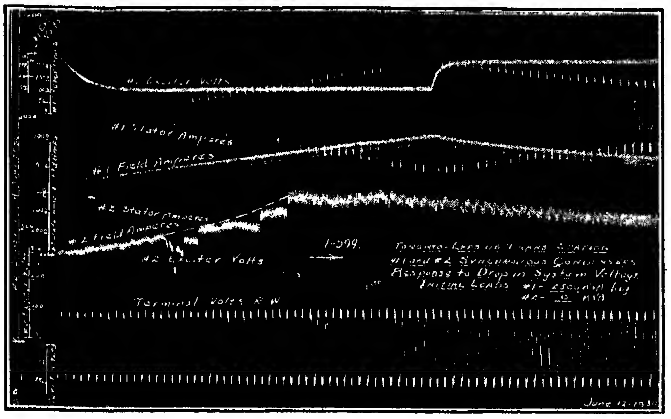

Fig. 1

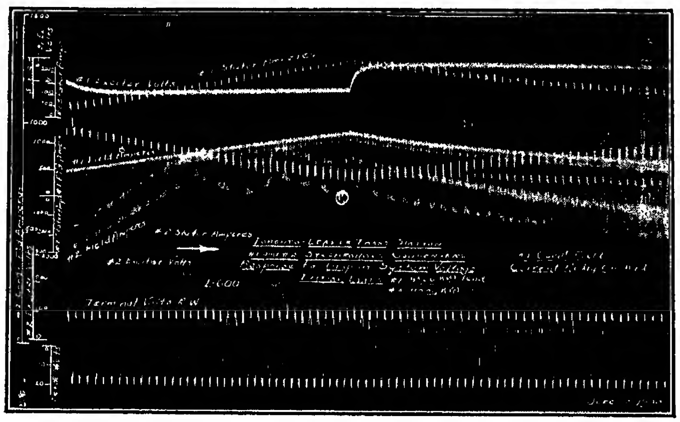

Fig. 2

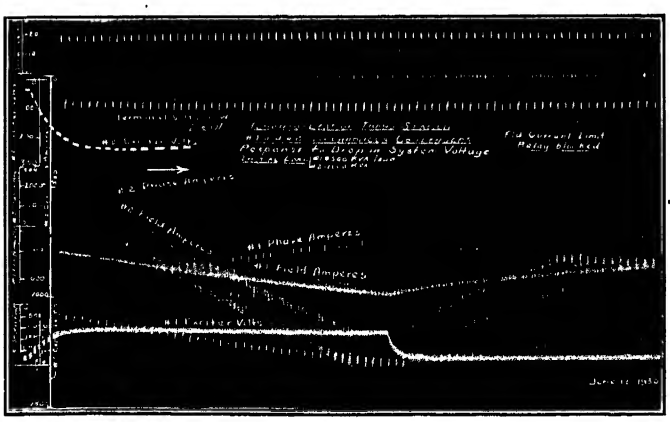

Fig. 3

drop in voltage, artificially produced, the condensers initially operating at practically zero load. These condensers are provided with a field limiting relay which prevents the field current from rising beyond a predetermined value. During the tests, No. 1 condenser was operating with this field current limiting relay blocked and No. 2 condenser was operating normally.

It is usual to express the quickness of response of synchronous condensers by the rate of rise of the exciter voltage. This record indicates that a better method of so rating a condenser would be to express the response by the rate of rise of the condenser field current or better, by the rate of rise of condenser kv-a. It will be noted that although the exciter voltage rises within a few cycles to its ceiling value, the field current of the condenser is much slower in response.

Fig. 2 is similar to Fig. 1 except that approximately 40 per cent of rated kv-a. leading was being carried by each machine initially.

Fig. 3 shows the response of the two condensers to a drop in system voltage when the field current limit relays of both units had been blocked. This test was made to determine whether the condensers could be operated together and would respond approximately equally to a drop in system voltage.

Data worked up from these tests indicates that the response of the two condensers is approximately the same, being at the rate of approximately 20,000 kv-a. per second if the abnormal condition is limited to about 2 seconds. The rate of response appears to be about the same whether the condensers are operating initially at lagging power factor or at leading power factor.

No. 220-kv. faults have occurred since these condensers went into service, but they have performed very satisfactorily through several 110-kv. faults.

It would appear that the chief advantage of their quick response characteristics would be during faults on the 110-kv. system west of Toronto, in which case they should assist materially in maintaining the voltage at the point of interconnection of the 110-kv. and 220-kv. systems. With the high speed of clearance of 220-kv. faults contemplated at the present time, it would appear from the data obtained that the condensers would hardly have time to respond before the fault would be cleared. There would be no necessity however, for them to do so.

L. W. Riggs: The authors have written a very interesting paper and have shown great resourcefulness and ability in their design.

Outdoor synchronous condensers seem to be a logical development, and, as operating experience is gained, the demand for such machines will no doubt increase.

The General Electric Company has built several outdoor synchronous condensers, some of which are hydrogen cooled, others of which are air cooled. All of them are of the horizontal shaft type.

In general, vertical machines cost more than horizontal machines. They are also usually more difficult to ventilate due to supporting structures for bearings impeding the flow of air.

There are many possibilities of varying the design of the exterior parts to suit any weather or ventilating conditions that may be encountered. One of the best designs is to re-circulate the air through surface water coolers when cheap water is available. Other layouts may incorporate air conditioning apparatus either in the machine housing or in a separate structure. If the air is reasonably clean, however, it is no more necessary to condition the air for an outdoor machine than for the large number of indoor machines that are now taking their air supply from outdoors.

The General Electric Company has been using springs under field coils for a number of years and has found them to be effective in automatically taking up any expansion of copper or shrinkage of insulation that may occur in the field coils.

The problem of predicting the best value of field current to use during the change from starting to running position is quite complicated due to the many interdependent variables. A little experimenting by the operator, however, will quickly determine a satisfactory value.

The East River Generating Station
of the New York Edison Company

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Synopsis.—This paper deals with the design and operating characteristics of the East River Generating Station of the New York Edison Company. This station, having an ultimate capacity of 1,240,000 kw., occupying as it does a site approximately a quarter of a mile long by 200 ft. wide, presents a number of design and operating features which are a departure from normal practise. Among the items of particular interest are:

1. The location of all of the circulating water pumps in a pit at the river end of the station, each set of pumps supplying its condenser through cast iron circulating water pipes six feet in diameter.

2. The adoption of steam turbine drive for the essential auxiliaries.

3. The adoption of pulverized fuel firing in what had hitherto been an exclusively stoker territory.

4. The burning of pulverized coal in a completely water cooled furnace containing practically no refractories.

5. The use of the largest boiler yet built.

6. The first use of a double winding generator which is also the largest generator in operation.

The paper presents some of the major considerations influencing the decisions reached on these items of design and the extent to which the expectations of the designers have been realized.

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THE New York Edison Company and affiliated companies operate two 25-cycle stations aggregating 402,000 kw., four combined 25- and 60-cycle stations aggregating 1,110,000 kw., and two 60-cycle stations aggregating 405,000 kw., a total generating capacity of 1,917,000 kw. with a 1929 peak load of 1,225,200 kw.

All stations are interconnected by means of tie feeders which approximate, in each instance, the capacity of the largest unit. Five frequency changers with a total capacity of 190,000 kw. tie the 25- and 60-cycle systems.

The arrangement of connections for the entire New York Edison System showing the relation thereto of the East River Station is given in Fig. 1. The 25-cycle system is operated radially, the high-tension feeders not normally being paralleled on the a-c. side of the rotary converters at the substations. The substations are usually supplied from more than one generating station to assure continuity and to facilitate load transfer.

The 60-cycle system is operated in parallel at the load (synchronized at the load), each section in a generating station being considered electrically as a separate station with ties only at the substation low-voltage busses or at the network.

At the time East River Station was designed, Manhattan Island was served almost exclusively from the 25-cycle system with conversion to direct current. The policy of the company at the present time, however, is to curtail the d-c. load in favor of the 60-cycle network. This paper deals with the development of the East River station as originally planned under a proposed growth of the 25-cycle system. Under the present policy of the company, no additional 25-cycle units will be installed, and the future development of the station will be devoted exclusively to 60 cycles. It is

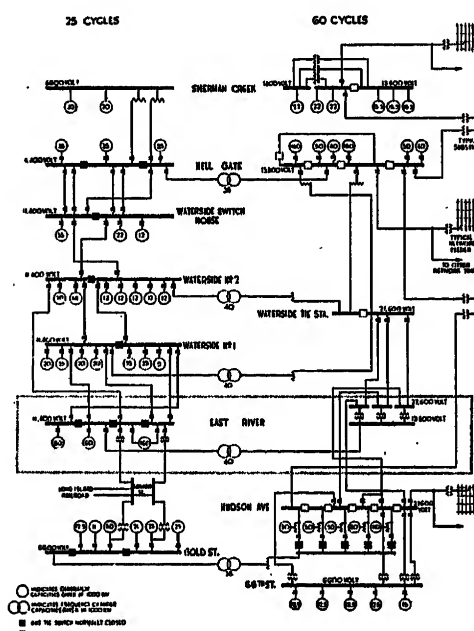

FIG. 1—SYSTEM CONNECTIONS

estimated that in 10 years the 60-cycle load of the New York Edison System will be at least four times the 25-cycle load.

SITE

There were very few areas on Manhattan Island where sufficient space together with other essential requirements satisfied the specifications for the station contemplated. The site chosen has the following advantages: it is near the center of the Manhattan load; it provides a continuous area for future expansion both

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

as to buildings and high-tension feeder outlets; favorable waterfront conditions provide ample water depth, some thirty feet, for docking ocean going colliers and for large disposal of ashes.

The arrangement of the buildings and structures is shown in Fig. 2. The generating plant, which lies between 14th and 15th Streets, Avenue C and the

Coal Handling and Preparation

The coal is at present brought to the station in 1000-ton barges and unloaded by two electric traveling coal towers each having a capacity of 350 tons per hour. The coal is crushed in the towers and discharged to belt conveyors for delivery to the 5000-ton bunker in the coal preparation house.

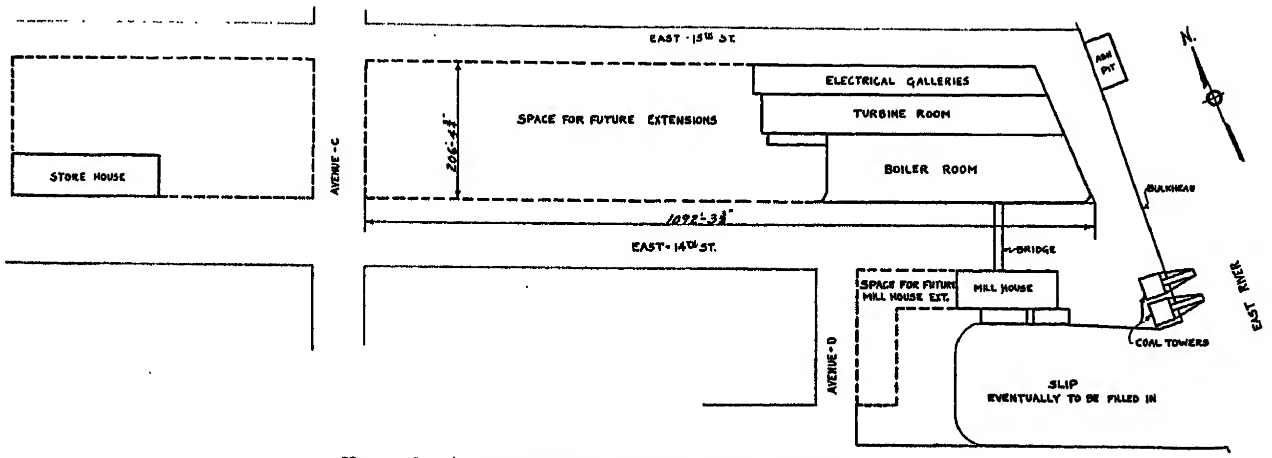

Fig. 2—Arrangement of Buildings on Site

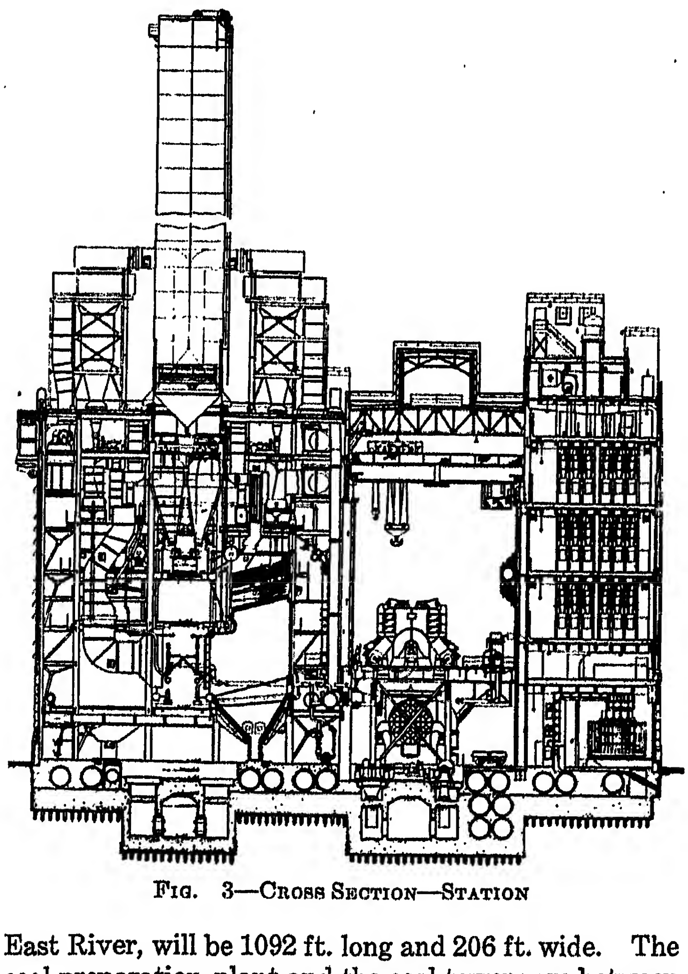

Fig. 3—Cross Section—Station

East River, will be 1092 ft. long and 206 ft. wide. The coal preparation plant and the coal towers are between 13th and 14th Streets, Avenue D and the East River. A cross-sectional elevation of the original installation is shown in Fig. 3.

The pulverizing equipment consists of two 15-ton and four 25-ton Raymond air-swept mills, the drying being accomplished therein by the admission of preheated air. The coal is fed into these mills by gravity through individual chutes from the raw coal bunker, the quantity being regulated by star feeders of which there are two per mill. Each mill has six rollers, 20 in. in diameter, each weighing 700 lb.

The air required by each 15-ton mill is supplied by a 28,000 cu. ft. per min. constant speed, motor-driven fan which operates in a closed system comprising the mill, the cyclone separator, and the fan. Adequate drying of the coal is obtained by means of preheated air drawn by a 14,000 cu. ft. per min. fan through a low-pressure heater at 15 lb. gage and a high-pressure heater at 400 lb. gage. The temperature of the air and coal leaving the mill does not exceed 105 deg. fahr. To compensate for this hot air introduced, an equal amount is exhausted from the system by another 14,000-cu.-ft.-per-min. fan. This exhausted air is passed through an additional cyclone separator for removal of the coal, which is led back into the system, while the air is vented through a U-shaped water spray air washer, (Fig. 4). With this method of coal drying, precautions must always be taken to start the heater fan before turning on the steam to the heaters to prevent fires due to dust collection on the tubes.

The arrangement of the 25-ton mills is similar, their larger fans being equipped with variable-speed instead of constant-speed motors.

The coal collected in the cyclone separator of the closed system flows by gravity into a transport pump which conveys it to the boiler coal bins. One 100-ton

coal bin is provided for each of the original boilers and two for each of the new boilers.

The average fineness of the coal is approximately 96 per cent through a 60-mesh, 90 per cent through a 100-mesh, and 70 per cent through a 200-mesh sieve. The moisture content of the coal affects the capacity of the mills to a certain extent but the grain characteristics of the coal itself have a far greater effect than the varying surface moisture.

Boilers and Fuel Burning System

The initial boiler installation consisted of six 14,809-sq-ft., Springfield, horizontal cross-drum boilers, 4134 sq. ft. of water wall surface on all four sides of the furnace and a slag screen above the ash pit. The superheater contains 3430 sq. ft. of heating surface and is of the hairpin type, while the air preheater contains 28,900 sq. ft. of effective heating surface and is of the stationary plate type. The Lopulco system of vertical firing with ten main burners and ten auxiliary burners is used (Fig. 5).

The new installation consists of three 800,000-lb. per-hr. boilers of the Ladd type fired from both ends. Each boiler contains 60,706 sq. ft. of heating surface and 7345 sq. ft. of water wall surface on all four sides of the furnace, with a slag screen above the ash pit (Fig. 6). The superheater contains 13,900 sq. ft. of heating surface and is of the hairpin type. The air preheater contains 82,721 sq. ft. of effective heating surface and is of the plate type. The furnace has a volume of 38,200 cu. ft. with a heat liberation of 29,300 B. t. u. per cu. ft. of furnace volume when operating at 800,000 lb. steam per hour. The steam conditions are 425 lb. gage pressure with 725 deg. fahr. total temperature, and feed water temperature of 360 deg. fahr. at 800,000 lb. per hour evaporation. The air temperature leaving the air preheater at this rating is 450 deg. fahr. The Lopulco system of vertical firing is used, with a total of 20 main and 20 auxiliary burners, or 10 of each on each end.

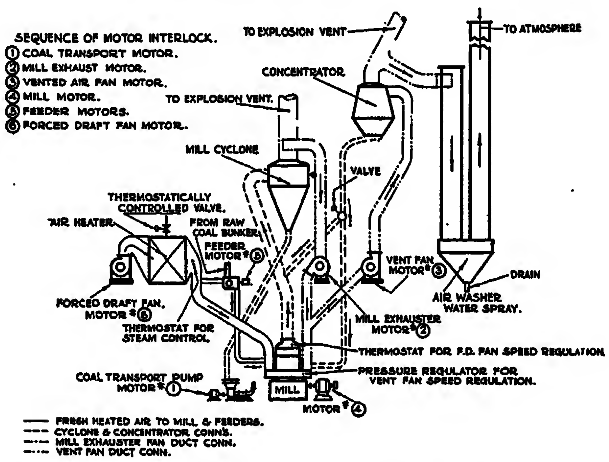

Fig. 4—Pulverizing Fuel Equipment for 25-Ton Mill

Subsequent to the initial starting period operating difficulties have been of a minor nature, little clinker trouble having been experienced either on the boiler tubes or the lower water wall headers. Any accumulation of ash or slag on the lower headers or sides of the ash pit is removed by means of a hand lance, while the boiler is in operation. Experience with the fin type tube indicates that the fins should not exceed one inch in width.

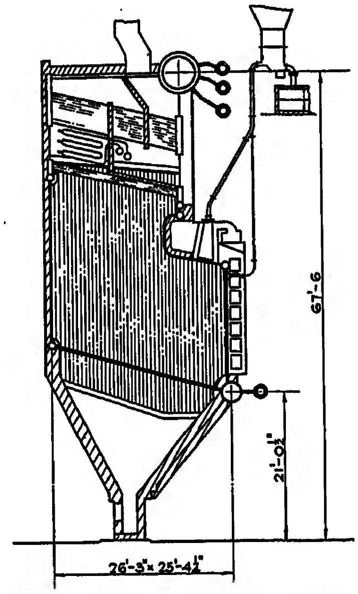

Fig. 5—Cross-Section Old Boiler Units

Some trouble was experienced in maintaining the water level in the top drum of the boilers but the addition of a plate baffle in the drums has corrected this condition for any load up to 600 per cent of boiler rating. The normal operating rate of these boilers is approximately 350 to 400 per cent. Table I gives the principal data from a test of No. 4 boiler.

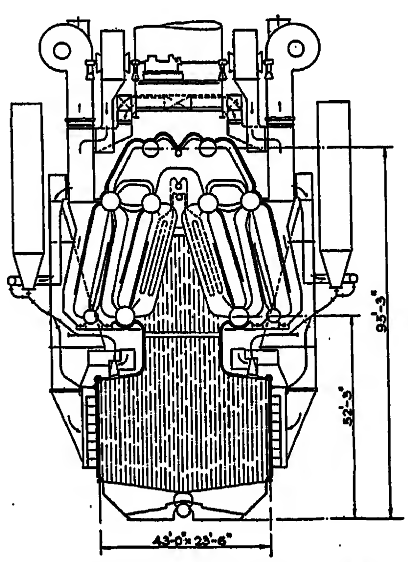

Fig. 6—Cross-Section New Boiler Units

Superheaters are installed in all boilers. The results obtained have been on the whole satisfactory, both as to the superheat output conditions and maintenance. The main trouble experienced has been leaking of ball and socket joints, since remedied by the use of copper gaskets.

The plate type air preheaters have given very good service. No sticking of clinkers has been experienced, nor have any elements required replacement since the station has been in operation. The passage of cinders with the gases has kept the plates clean, and there has been no evidence of corrosion or erosion.

The draft equipment, which consists of induced draft, primary and secondary air fans has given very good service. The only trouble experienced is with the induced draft fans, the blades and scroll linings of which have to be replaced every two years due to the erosive action of the cinders.

Pulverized fuel was adopted for this station for the following reasons:

1. It was believed that this type of firing would permit a very much larger field from which to purchase suitable coal and that high efficiencies could be maintained with some of the cheaper grades of coal which can be burned only with great difficulty on stokers.

2. Our experience with large stoker fired boilers indicated that with such equipment, we must expect to have from 10 to 15 per cent of the boiler capacity continuously out of service for repairs. It was felt that with pulverized fuel firing, this outage would be very largely eliminated, resulting in the installation of less boiler capacity to meet a given load.

3. The experience of others in burning pulverized fuel indicated a much flatter efficiency curve than with stoker firing.

4. On account of the close proximity of the station to the congested sections of New York City, it was deemed essential that every effort be made to eliminate any possible nuisance due to the emission of smoke and cinders from the stack. It was felt that objectionable stack discharges would be more easily controlled from pulverized fuel than from stoker firing.

Our operating experience to date indicates that the field from which we can buy our coal supply includes any place in the world that can produce coal. We are now buying coal of equal heat value for this station at a cost of 24 cents per ton less than we are paying for stoker plants. This differential more than offsets the cost of coal preparation which averages about 18.5 cents per ton including labor, maintenance and power (at fuel cost) and in addition to this advantage, the repairs to the boiler and furnace due to the use of the completely water-cooled walls, is almost nothing compared to the repair costs on stoker fired plants.

The degree in which our expectations have been realized in the elimination of boiler outage for repairs, is illustrated by the fact that for a period of eight months last year, none of the boilers in this station was out for repairs other than between midnight and 6 a. m. on week days and on Sunday during periods of light load.

It will be seen from Table I, that the small boilers have a very flat efficiency curve, there being only 2 per cent difference in efficiency between an output of 108,000 lb. of steam per hour and an output of 240,000 lb. of steam per hour.

A test was recently run on one of the new boilers which was designed for a maximum capacity of 800,000 lb. of steam per hr. on which an output of 1,000,000 lb. of steam per hr. was maintained continuously for twelve hours with entirely stable furnace and water level conditions and with no signs of distress in any part of the equipment. A heat balance of this run is given in Table II indicating an efficiency of 86.5 per cent at an output of 25 per cent above the maximum guaranteed capacity, thus amply justifying our expectations for high sustained efficiencies. An output of 1,250,000 lb. per hr. has been maintained on one of these boilers for one hour and 15 minutes accompanied by a slight drop in efficiency.

With the exception of the first few months of operation, while initial adjustments of the equipment was being made, we have had no complaints due to either smoke or cinders from this station. The efficiency of the electrostatic and cyclone dust catching apparatus is such that we have been unable to locate any deposits of flue dust in the surrounding neighborhood.

Up to the time when this station was designed, practically all pulverized fuel furnaces had been very largely refractory lined and it was thought by designers that in spite of the high maintenance cost on such furnaces, a refractory lining was necessary to maintain stable fire conditions, particularly with low volatile coal. The furnaces in this station departed radically from previous designs in that they were completely water-cooled, in spite of the fact that our normal coal supply is of a low volatile character.

Considerable difficulty was experienced in the early stages of the station operation in maintaining stable firing conditions with the vertical burner system originally installed. After experimenting in various ways Mr. A. J. Wheeler, Jr., superintendent of the station, conceived and developed the idea that by applying a flame to the stream of coal immediately after its entrance to the furnace, combustion could be accelerated to a point where the heat radiated from the flame to the water-cooled walls did not reduce the flame temperature to a point where combustion was retarded.

Applying this principle, small auxiliary burners have been installed at right angles to each vertical burner, so disposed as to impinge on the stream of fuel leaving the vertical burner at a point slightly below its entrance into the furnace.

This method of burning coal has reduced the un-

TABLE I

		April 23, 1929	May 7, 1929	May 14, 1929
Actual evaporation per hour	lb.	108,630	169,100	239,720
Heat absorbed by steam	per cent	86.1	87.1	84.1
Heat absorbed by air preheater and returned to other boilers	per cent	2.0	0.5	1.0
Heat loss due to moisture in coal	per cent	0.2	0.3	0.2
Heat loss due to moisture in burning hydrogen	per cent	3.2	3.2	3.1
Heat loss due to dry chimney gases	per cent	6.0	7.3	6.1
Heat loss due to combustible in refuse	per cent	0.8	0.8	2.5
Heat loss due to radiation and unaccounted for	per cent	1.7	0.8	3.0
Total	per cent	100.0	100.0	100.0

		April 23, 1929	May 7, 1929	May 14, 1929
Actual evaporation per hour	lb.	108,630	169,100	239,720
Boiler horsepower		3,545	5,715	7,885
Per cent rating (including water walls)		187	302	416
Per cent rating (excluding water walls)		240	386	532
Steam pressure, boiler-gage	lb. per sq. in.	404	414	425
Steam pressure, superheater outlet	lb. per sq. in.	398	399	400
Steam temperature	deg. fahr.	685	711	710
Air to air preheater	deg. fahr.	106	108	111
Average temperature of gases leaving air preheater	deg. fahr.	328	382	368
Temperature feed water	deg. fahr.	293	294	298
Fuel, as fired per hour (weighed)	lb.	10,030	15,650	22,200
Fuel dry, per hour	lb.	9,740	15,060	21,080
Combustion space per lb. dry coal	cu. ft.	1.63	1.05	0.73
Actual evaporation per lb. dry fuel	lb.	11.15	11.23	10.99
Actual evaporation per lb. fuel as fired	lb.	10.82	10.80	10.80
Factor of evaporation		1.126	1.137	1.135
Equivalent evaporation per lb. dry fuel	lb.	12.48	12.76	12.47
Thousands B. t. u. absorbed per hour		118,730	186,520	263,810
Thousands B. t. u. absorbed per sq. ft. boiler heating surface including water walls		6.27	10.40	14.37
Refuse, per cent of fuel, dry		9.1	8.7	10.4
Per cent combustible in ash to ash pit		1.0	0.8	2.1
Per cent combustible in fly ash		9.7	10.0	25.8
Per cent combustible in refuse		8.8	9.1	23.3

		Semi-bituminous storage	Semi-bituminous storage	Semi-bituminous fresh mined
Proximate analysis dry:				
Volatile matter	per cent	18.8	19.2	19.5
Ash	per cent	8.3	7.9	8.0
Fixed carbon	per cent	72.9	72.9	72.5
Moisture—as fired	per cent	2.9	3.8	1.9
Heating value per lb. dry	B. t. u.	14,140	14,220	14,410
Ultimate analysis:				
Carbon	per cent	80.65	80.60	80.70
Hydrogen	per cent	4.25	4.28	4.29
Oxygen	per cent	4.70	5.22	4.38
Nitrogen	per cent	1.25	1.22	1.25
Sulphur	per cent	6.89	0.78	1.36
Ash	per cent	8.28	7.90	8.02
Fineness:				
Through 60 mesh screen	per cent	92	95	80
100 mesh screen	per cent	85	89	69
200 mesh screen	per cent	72	73	54

TABLE II
HEAT BALANCE OF NO. 7 BOILER—OUTPUT 1,000,000 LB. PER HR.

	B. t. u.	Per cent
Loss due to moisture in coal	11	0.1
Hydrogen	453	3.0
Dry chimney gases	1,137	7.7
Combustible in refuse	73	0.5
Moisture in air	30	0.2
Radiation and unaccounted for	294	2.0
Total losses	1,998	13.5
Efficiency and heat to boiler	12,772	86.5
Total	14,770	100.0

burned carbon losses, increased the furnace capacity, eliminated all slag trouble, and made possible stable firing conditions at all rates of operation.

Ash Handling

The ashes from all the boilers are drawn into trenches running along both sides of the boiler room. They are sluiced along these trenches to a central ash pit into which the ashes collected from the cyclone separators and precipitators are also discharged. Centrifugal pumps remove these to a large concrete ash hopper on the dock from which they are loaded into scows by gantry cranes. Approximately 80 to 90 per cent of the ashes pass up through the boiler, the remaining 10 to 20 per cent being drawn from the ash pit.

Two types of cinder catchers are in use, cyclone separators and precipitators. A Davidson cyclone separator was installed on each of the first six boilers with satisfactory results. The only maintenance required has been the relining of the helix after two years of service. Two Cottrell precipitators have been installed on each of the three new boilers. They are

giving excellent service, test runs showing efficiencies of 90 to 95 per cent.

Generating Equipment

The generating building will have accomodations for nine steam turbo generators of large capacity, three of which are already in operation. The first, of 60,000-kw., designated Unit No. 2 went into service November 19, 1926; the second, a 60,000-kw., Unit No. 1, on

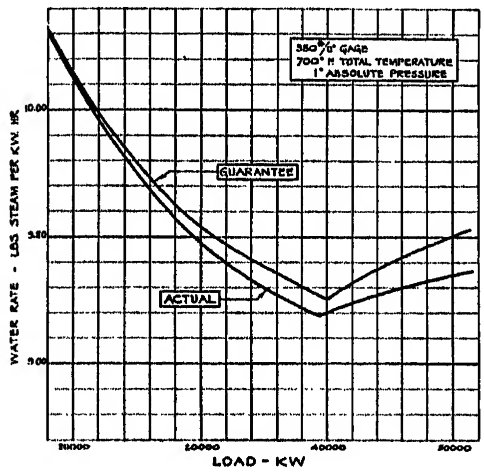

Fig. 7—Steam Rate Curve Turbines No. 1 and 2

February 21, 1927; the third, a 160,000-kw. Unit, No. 4, on October 10, 1929. This unit which has a tandem compound turbine, using straight steam flow on the high pressure and double flow on the low pressure, has been operating very satisfactorily. To date no water rate tests have been made on this unit. (See Figs. 7, 8, and 9.)

The generated potential is 11,400 volts, three phase,

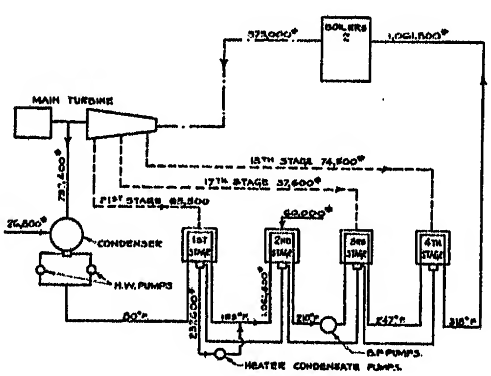

Fig. 8—Heat Balance—Unit No. 4

25 cycles. All 25-cycle energy is transmitted at this voltage except for two 33-kv. feeders which tie through Lorimer Street substation with the Brooklyn Edison Company's Gold Street Generating Station and serve both as a supply to the Long Island Railroad and as a means of interchanging power between the generating stations. Three 15,000-kv-a. transformers step up the energy from the 60-cycle end of the frequency changer to 27,600 volts.

While it is expected that all future additions to this station will be for 60-cycle operation, the future operating voltage has not as yet been determined.

Excitation Supply

Excitation for the main units is furnished exclusively by direct-connected exciters, each exciter being con-

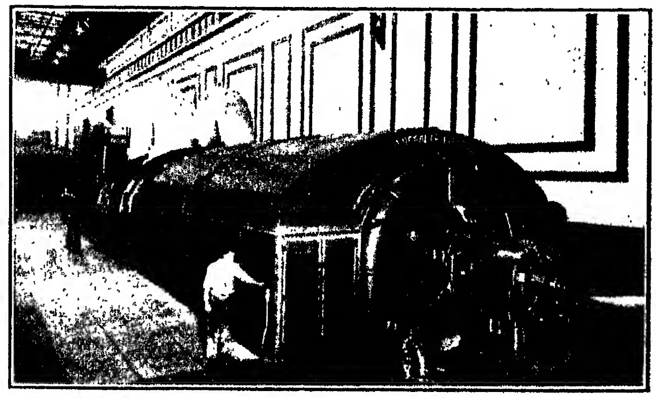

Fig. 8—160,000-Kw. Generator

nected solidly to the main field through the main field rheostat. The exciter field circuit is equipped with remote control air circuit breakers which are automatic in operation when actuated by the over-all differential relay of the main unit.

The exciter field breakers of the 160,000-kw., two-winding generator No. 4 are tripped automatically also by the winding differential relay. The main and exciter field rheostats and the exciter field breakers are controlled from the generator control panel in the high-tension switchboard room.

Frequency Changer

A 40,000-kw. frequency changer, designated Unit No. 3, is of the synchronous induction type. The 60-cycle induction generator excited by means of an 18,500-kw. transformer from the 25-cycle system provides a transformer tie as well as a power tie, (Fig. 10).

The frequency changer was installed for a twofold

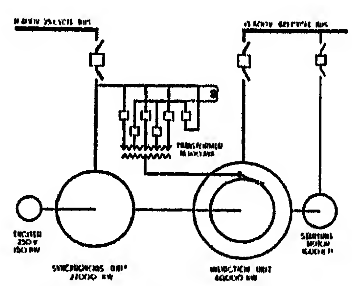

Fig. 10—Frequency Changer Connections

purpose, first, to make possible the pooling of the spare capacity on the 60-cycle and 25-cycle systems, and second, to maintain the two systems in synchronism.

At the time the frequency changer was installed, the rotary converters supplying the d-c. network were all

25-cycle machines, but it was thought that in view of the pronounced trend toward 60 cycles as a standard frequency it might become desirable in future installations to use 60-cycle converters. In order to obtain satisfactory operation of the two types of rotary converters it was realized that it would be essential to keep the two systems in synchronism and that, furthermore, to prevent possible damage to the commutation equipment, the tie between the two systems should be as strong as possible. It was with this thought in mind that the synchronous induction type of frequency changer was chosen. Although the anticipated use of the 60-cycle rotary converters has not developed due to the expansion of the a-c. network system in Manhattan, it is felt that the use of the synchronous induction type of frequency changer has been of advantage in increasing the stability of operation between the two systems. By taking advantage of this it is possible to keep on the system only such frequency changer capacity as may be required for load interchange without operating additional machines for the sole purpose of maintaining synchronism. In view of the magnitude of the two systems it is felt that the performance from this point of view has been very gratifying.

Condensers

The condensers for the three units are all of the single-pass, surface type, those for Units No. 1 and 2 having 47,500 sq. ft. of surface and that for Unit No. 4, 90,000 sq. ft. of surface. Each condenser has two circulating water pumps which are all located in a pump room at the east end of the turbine room basement, adjacent to the water front. The water is pumped through cast iron pipes, 72 in. in diameter, embedded in the concrete mat, to the perspective condensers, the length of these pipes varying with the distance from the pumps. The last unit to be installed in the station will be approximately 1000 ft. away from the pumps. The overboard water from the condensers is discharged through individual 72-in. pipes to the river.

Units No. 1 and 2 each have two hot-well pumps while Unit No. 4 has three hot-well pumps. Steam jet vacuum pumps are used on all of the condensers.

Considerable initial wear at the inlet ends of the tubes in the condensers for Units No. 1 and No. 2 have been corrected by means of 12-in. inserts. This, together with the removal of accumulated air or gases from the tope of the inlet water box by means of a connection to the tope of the tail pipe, has greatly lessened tube failures.

The tubes are cleaned by shooting a mixture of sand and pulverized fuel ash in equal proportions, and water through the tubes by means of compressed air. The cleaning is done by sections whenever the turbines are shut down, usually on the 12:00 midnight to 8:00 a. m. watch or on Sundays.

Four stages of feed water heating is the practise at the East River Station, three by steam bled from the main units and one by the exhaust steam from the steam auxiliaries. Units No. 1 and 2 are bled from the 11th, 14th, and 18th stages and Unit No. 4 from the 13th, 17th, and 21st stages. The cycle of feed water heating is given in the accompanying typical heat balance for Unit No. 4.

Auxiliaries

Steam driven auxiliaries are used for the circulating water, boiler feed, and condensate pumping. The primary air, secondary air, and induced draft fans are also steam driven, thus providing a very even acceleration or deceleration of speed.

The non-essential auxiliaries, or those which may be shut down for short periods of time without affecting service, such as pumps for ash pit, house service, hot-well test, storage tanks, fire lines, dust precipitators, coal towers and powdered fuel mills, are supplied from 2300-volt or 440-volt 25-cycle busses energized from house transformers on the main bus. These house busses also supply motors for ventilating fans for the main generator and frequency changers and other auxiliaries with similar duplex drives (steam and electric).

The transformers are supplied from different sections of the main bus and house busses are operated radially although provision has been made for parallel operation either as a solid bus or sectionalized by reactors.

A 125/250-volt d-c. house bus supplied from geared cross connected turbo generator units is provided for the operation of boiler fuel feed. The fuel feed motors of each boiler are supplied from a motor generator set connected to the d-c. house bus and provided with a Ward Leonard automatic control. The 250-volt bus also furnishes all building lighting and some small miscellaneous power. As a standby to the turbo-generator units there is a 2240-ampere-hour battery capable of maintaining full emergency load for one-half hour.

It was considered that the auxiliary drive system for a station such as this, designed to supply a large d-c. system, to be satisfactory from the standpoint of reliability, should be supplied from such sources that in the case of a break in any steam line, a shut-down of all the main generator units, a shut-down of any one auxiliary unit or the shut-down of the main bus would not interrupt the operation of the auxiliaries to more than one generating unit. It is recognized that these assumptions may not necessarily apply to other projects or to present day conditions in the territory served.

The careful study of all the systems in use at the time indicated that the following systems met the above requirements:

A. Steam turbines.

B. D-c. electric supply from the main bus with storage battery reserve.

C. A-c. electric supply from shaft alternators with main bus and house alternator reserve.

Designs and cost estimates were made for each of these three systems. These cost estimates indicated

that the a-c. electric supply systems would cost 35 per cent more than steam turbines and the d-c. system 120 per cent more than steam turbines. (Electric supply estimates include a charge of $40.00 per kw. for electric generating capacity used for auxiliaries.) Heat balance calculations indicated that the additional fuel consumption of the steam drive system would if capitalized, reduce the above differential in the case of a-c. drive two per cent and with direct current three per cent.

Steam drive for these auxiliaries has been entirely satisfactory from the point of view of reliability. The steam consumption, however, is somewhat higher than the original calculations.

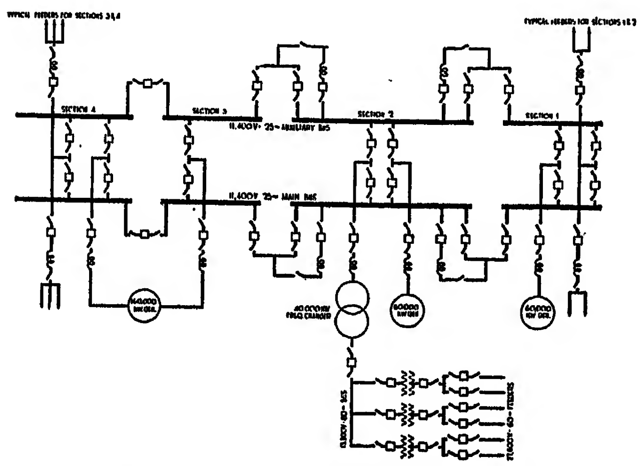

FIG. 11—STATION BUS ARRANGEMENT

ELECTRICAL EQUIPMENT OF 160,000-KW. UNIT

The main and emergency busses for the first two 60,000-kw. units were sectionalized,—one section for each generator with its complement of feeders, the sections being connected through 10 per cent reactors based on the full load of a generator.

In the latest addition, the one 160,000-kw. unit is of the single shaft type and due to the high current of a unit of this size it was impossible to procure single generator switches of sufficient carrying capacity. It was therefore necessary to consider two switches in parallel. The use of a double winding generator, however, provided a very simple means of assuring satisfactory load division between the output circuits and at the same time reduced the current capacity and interrupting duty on the switches, (See Fig. 11.) In this unit the windings in alternate slots are connected to separate circuits and the circuits alternated under adjacent pole faces, thus distributing the circuits and producing balanced magnetic forces. This method of winding results in an added number of end connections and leads, but is otherwise identical with a standard single winding unit.

It may be interesting to digress for a moment at this point to consider the application of such a unit to the general layout of a system. The increase in capacity of units, stations, and systems in recent years with the consequent requirement of greater interrupting capacity of circuit breakers and other costly problems resulting from excessive currents and high magnetic forces has brought to the art entirely new conceptions of station bus layouts, all tending toward the splitting up of stations into small sections which may in themselves be considered as separate generating stations.

The first of these new designs was incorporated in the Hudson Avenue Station of the Brooklyn Edison Company in which the individual generator sections are synchronized only through a high-reactance synchronizing bus. Following this point, synchronizing was carried to the substations, whereas in the case of the United Electric Light & Power Company the generator sections were synchronized at the load in the network area or at the secondaries of the substation transformers in other areas, the reactance between bus sections being even higher in this scheme than in the case of the synchronizing bus.

The double winding generator through its transformer action creates a very high reactance between windings (equivalent to generator bus sections) but due to the linkage of a common field the stability is not decreased by this increase in reactance. In large sized generators it seems feasible to increase the number of windings which may be brought out of a unit and by use of multiple windings in conjunction with the scheme of synchronizing at the load to still further reduce the magnitude and extent of short-circuit disturbances and at the same time to improve system stability.

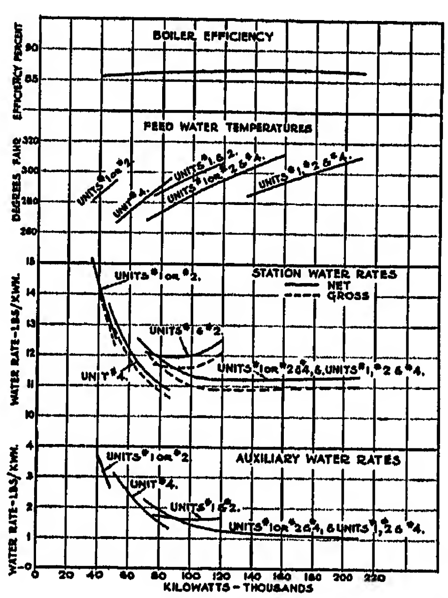

FIG. 12—STATION PERFORMANCE DATA

For the one 160,000-kw. unit at East River it was, however, possible to use only the high reactance sectionalizing due to double windings as the 25-cycle system is not operated as a parallel system at the substations. While there were no immediate economies over the previous layout of one generator to a section

with 10 per cent sectionalizing reactance, the adoption of the double winding design looked forward to future economy due to the elimination of bus tie switches and reactors. The decrease in maximum instantaneous short-circuit duty from approximately 2,500,000 kv-a. to 1,500,000 kv-a. was one of the outstanding advantages of the new design.

Feeder Arrangement

In order to still further reduce the number of switches required, outgoing feeders were grouped together. The H arrangement was used in this station with two selector and two feeder switches per group. The standard feeder is 350,000 cir. mils and supplies one 4200-kw. converter in a substation. In the first two sections of East River, double feeders were used, the bifurcation being made at some remote point in the street and in the last section triple feeders were similarly employed, the new groups now serving six normal feeders or a connected load of 25,000-kw. direct current (approximately 32,000-kw. high-tension alternating current.)

Electrical Galleries

The electrical galleries are of the vertical isolated phase type; there are few special features incorporated which are not common to all modern isolated phase galleries. The long narrow formation of the building permits economical grouping of compartments and easy physical separation of generator sections; the busses, main and emergency, are mounted on the two sides of the room with about 30 ft. separation but this separation cannot be maintained in the selector switches. All busses and bus connections are bar copper mounted on 25,000-volt insulators but in addition all copper is wrapped with varnish cambric to a thickness equivalent to 15,000-volt insulation in order to minimize possible short circuits due to gases which might be present as the result of minor disturbances. All feeder cables are single conductor lead, both in the station and in the adjacent streets and no cable joints are made within the station.

General Design Features of 1929 Extension

When it was decided to go ahead with the first extension of this station, it was found that turbine builders were prepared to supply single turbo generators, having a capacity of 160,000 kw. each, at a considerably lower cost per kw. than for the 60,000-kw. units in the original installation. It was then decided that in the extension of this station, the same number of units as originally planned would be installed, but that these units would have nearly three times the capacity of the original units. The manner in which this has been accomplished is illustrated by the following figures:

Turbo generators Nos. 1 and 2 (60,000-kw. capacity each) occupy 0.083 sq. ft. per kw. capacity, while turbo generator No. 4 (160,000-kw. capacity) occupies 0.0452 sq. ft. per kw. capacity. Boilers 1 and 6 (250,000-lb. capacity each) occupy 9.2 sq. ft. and 1140 cu. ft. per 1000-lb. steam capacity. Boilers 7, 8, and 9 (1,000,000-lb. capacity each) occupy 4.5 sq. ft. and 625 cu. ft. per 1000 lb. steam capacity. Similarly the electrical galleries for generators No. 1 and No. 2 require 0.48 sq. ft. of floor area and 7.39 cu. ft. per kw. capacity, whereas similar equipment for generator No. 4 occupies 0.215 floor area and 3.92 cu. ft.

Station Operating Data

Fig. 12 shows in graphic form boiler efficiency, feed-water temperatures, total station and auxiliary water rates of this station when carrying loads from 35,000 to 210,000 kw. These curves are based on the station performance for the months of February and March 1930. The station heat rate is 15,000 B. t. u. per net kw-hr.

	UNITS NO. 1 AND 2	UNIT NO. 4
Boilers—Superheaters and preheaters		
Type of boilers	Springfield, horizontal, cross-drums. Water cooled walls	Combustion Engg. Corp. Water cooled walls
Number installed	6	3
Heating surface per boiler, sq. ft.	14,809	60,706
Heating surface of water walls per boiler, sq. ft.	4,134	7,345
Furnace volume, cu. ft. above water screen	15,888	38,200
Furnace volume, cu. ft. below water screen	4,969	
Boiler pressure, lb. gage	410	425
Superheat, deg. fahr.	257	271
Total steam temperature, deg. fahr.	700	725
Superheater, location	Superheater Co. Between upper and lower bank of boiler tubes in first pass	Superheater Company. In first pass
Superheating surface per boiler, sq. ft.	3,430	13,900
Air preheater, type	Combustion Engg. Corp. Stationary steel plate	Combustion Engg. Corp. Stationary steel plate
Heating surface of air preheater per boiler, sq. ft.	28,900	82,721

	UNITS NO. 1 AND 2	UNIT NO. 4—Continued
	Stack and Draft Equipment	
Type of stack	Steel, unlined	
Number	2	
Diameter, inside ft	22	
Height above basement floor, ft	376.5	
Support	On building steel	
	Induced Draft Fans	
Induced draft fans	B. F. Sturtevant Co. 150,000 cu. ft. per min. at 8.5 in. static pressure	B. F. Sturtevant Co. 260,000 cu. ft. per min. at 17 in. static pressure
Number per boiler	1	2
Drive	Sturtevant turbine and gear. 400 hp. turbine	Sturtevant turbine and gear. 1150 hp. turbine
	Forced Draft Fans	
Forced draft fans	Sturtevant—60,000 cu. ft. per min. at 6.4 in. static pressure	Sturtevant—125,000 cu. ft. per min. at 9 in. static pressure
Number per boiler	1	2
Drive	Sturtevant turbine and gear. 115 hp. turbine	Sturtevant turbine and gear. 263 hp. turbine
	Primary Air Fans	
Primary air fans	Sturtevant Co. 4-24,000 cu. ft. per min. at 18 in. static pressure. 1-22,000 cu. ft. per min. at 40 in. static pressure	Sturtevant Co. 54,000 at 25 in. static pressure
Number	5 for six boilers	4 for three boilers
Drive	General Electric turbine and gear. 4-125 hp. turbine. 1-230 hp. turbine	General Electric turbine and gear. 307 hp. turbine
	Dust Collectors	
Dust collectors—type	American Blower Co. Cyclone	Cottrell precipitator
	Raw Coal Handling Equipment	
Coal towers—capacity each, tons per hr.	Main Electric Co.—350	
Number	2	
Conveyors, capacity each tons per hour	Dodge Mfg. Co.—350	
Number	5 groups of 2 conveyors each	
	Raw Coal Handling Equipment Continued	
Bunker, capacity tons	5,000	
Outdoor coal storage capacity, tons, (future)	48,000	
	Pulverized Coal Equipment	
Pulverizers, type	Combustion (Raymond) Air swept (preheated air)	
Capacity, tons per hour Number	2-15 4-25	
Drive	Motor	
Transporter	1 per mill, motor driven	
Feeders—Number per boiler	10 Main 10 Auxiliary	20 Main 20 Auxiliary
Weigh bins, capacity each, tons	10	
Number	2	
Storage bins, capacity, each tons	100	1-115, 1-135
Number, per boiler	1	2
	Main Generating Units	
Capacity, kw	General Electric Co. 60,000	General Electric Co. 160,000
Number	2	1
Generators	3-phase, 25 cycle, 11,400 volts	3-phase, 25 cycle, 11,400 volts
Speed rev. per min	1,500	1,500
Exciter, type	Shaft driven	Shaft driven
Capacity, exciter (kw.)	200 kw., 250 volts.	250 kw., 250 volts
Generator ventilation, type	Closed system	
Steam conditions at turbine throttle	350 lb. gage 700 deg. fahr. total temperature	375 lb. gage 725 deg. fahr. total temperature
	Auxiliary Turbo Generators (Direct Current)	
Capacity, kw. (DeLaval turbine, Crocker-Wheeler generators)		500
Number		3
Generator	250-volt d-c. three-wire, 900-rev. per min.	
Steam conditions at turbine throttle	350 lb. gage, 700 deg. fahr. total temp.	

	UNITS NO. 1 AND 2	UNIT NO. 4—Continued
	Auxiliary Turbo Generators (Mill House)	
Capacity, kw. De Leval Turbine—General Electric Generator		1000 kw.
Number		1
Generator	3-phase, 25-cycle, 2300 volts, 750 rev. per min.	
Steam conditions at turbine throttle	350 lb. gage, 700 deg. fahr. total temperature	
	Main Condensers and Auxiliaries	
Condenser, type	Wheeler—Single pass	Ingersoll-Rand—Single pass
Tube surface, sq. ft	45,000—Condenser 2,500—Air cooler	90,000
Number per turbine	1	1
Circulating pumps—capacity each, G. P. M	Wheeler 45,000	Ingersoll-Rand 80,000
Number per condenser	2	2
Drive General Elec. Turbine and gear	300-hp., 6270-rev. per min. 3-stage condensing turbine	1200-hp., 7700 rev. per min.
Hotwell pumps—capacity each, gram per min	Wheeler 1,350	Ingersoll-Rand 2,000
Number per condenser	2	3
Drive Sturtevant Turbine and gear	76.5 hp. turbine	75 hp. turbine
Air pumps—type	Wheeler Steam jet	Ingersoll-Rand Steam jet
Number	1 for each unit	12 Primary Ejectors and 4 Secondary Ejectors
	Boiler Feed Pumps	
Capacity each gals. per min	Dean Hill 1200 gals. per min.	Dean Hill 2000 gals. per min.
Drive General Elec. Turbine and gear	505	1000 hp. turbine
Number	4	3
Discharge head	500 lb.	630 lb.
	Ash Handling Equipment	
Type of systems	Sluicing, pump, and hoisting	
Ash Gantry Maine Elec. Co	162 tons per hour	
Drive	100 hp. motor	
Ash Pumps 2—10 in. Morris Machine Work centrifugal pumps Manganese lined	Cap. 3200 gals. per min. against head of 35 ft.	
Drive	125 hp. motors	
	Generator Air Coolers	
	Turbines No. 1 and No. 2 and frequency changer General Electric—water cooled	Turbine No. 2 Griscom-Russell water cooled
	Frequency Changer (General Elec. Co.)	
Capacity	40,000 kw.	
Current characteristics	60 cycle end, 3-phase, 13,800 volts	
Current characteristics	25 cycle end, 3-phase, 11,400 volts	
Speed	300 rev. per min.	

Transformers

For excitation to 60-cycle end of frequency changer:
1—18,500 kv-a., 3 phase, 11,400/3300 volts, 25 cycle. (General Electric Company)
For supply to 60-cycle end of frequency changer
3—15,000 kv-a. 3 phase, 28,980/13,800 volts, 60 cycle. (Pittsburgh Transformer Co.)
Station Power:
3—4000 kv-a., 3 phase, 11,400/2300/440 volts, 25 cycle. (Pittsburgh Transformer Co.)
Interstation Ties:
2—18,000 kv-a., 3 phase, 11,400/34,500 volt, 25 cycle. (General Electric Company)

OIL CIRCUIT BREAKERS AND DISCONNECTING SWITCHES

	Quantity	Capacity	Type
For 27,600-volt, 60-cycle feeders (General Electric Co.)	9	600	Adjacent phase dead tank
For 13,800-volt, 60-cycle supply to frequency changer (General Electric Co.)	4	1,200	" " " "
	1	2,000	" " " "
For 11,400-volt, 25-cycle equipment—Sections 1 and 2 (General Electric Co.)			
Generator and bus ties	18	4,000	Segregated phase dead tank
Frequency changer	3	3,000	" " " "
Feeder selectors	26	1,200	" " " "
Feeders	26	800	" " " "

OIL CIRCUIT BREAKERS AND DISCONNECTING SWITCHES—Continued

	Quantity	Capacity	Type
For 11,400-volts, 25 cycle equipment, Sections 3 and 4:			
Generator and bus ties	8	5,000 Amperes	Segregated phase dead tank
Interstation tie selectors	4	3,000 "	" " " "
" " "	4	2,000 "	" " " "
Interstation feeders	2	2,000 "	" " " "
" "	2	1,200 "	" " " "
Feeder selectors	6	1,200 "	" " " "
Feeders	10	800 "	" " " "
For 2300-volt, 25-cycle Station Power Equipment (Westinghouse Elec. & Mfg. Co.):			
Transformer and bus ties	13	1200 Amperes	truck type
Feeder selectors	10	1,000 "	" "
Feeder selectors	8	600 "	" "
Feeders	5	800 "	" "
Feeders	13	400 "	" "
Feeders	32	200 "	" "
For 2300-volts, 25-cycle, Mill House Equipment:			
Generator (General Electric Co.)	1	500 Amperes	cell mounting
Group feeders (Westinghouse Elec. & Mfg. Co.)	8	400 Amperes	truck type
Feeders (General Electric Co.)	40	300 Amperes	cell mounting

REACTORS

For 11,400-volt, 25-cycle equipment (Metropolitan Device Corp.) Sections 1 and 2

	Quantity	Kv-a.	Amperes	Per cent reactance
Generators	6	1200	3040	6
Frequency changer	3	402	2030	3
Bus ties	12	2000	3040	10
Feeders	72	180	600	4.5
For 11,400-volt, 25-cycle equipment. Sections 3 and 4:				
Generator (Metropolitan Device Corp.)	6	1336	4060	5
Interstation ties " " "	6	595	1500	6
Interstation ties (General Electric Co.)	6	180	900	3
Feeders (Metropolitan Device Corp.)	30	405	900	6.8
For 2300-volt, 25-cycle station power equipment	6	57	1200	5

SWITCHBOARDS

Generator and frequency changer—Remote control electrically operated, bench-board type (General Elec. Co.)
H T Feeders—Remote control electrically operated vertical board type (General Elec. Co.)
Auxiliary power control—Remote control electrically operated, vertical board type (General Elec. Co.)
440-Volt A. C. Station power main—Remote control electrically operated vertical board type (Westinghouse Elec. & Mfg. Co.)
440-Volt A. C. Station power, distribution—Manually operated oil circuit breaker type (Westinghouse Elec. & Mfg. Co.)
250-Volt D. C. Station power—Remote controlled electrically operated circuit breakers, vertical board type (A. & J. M. Anderson Co.)

BATTERIES (E. S. Battery Co.)

1—For main station light and power—250-volt, 2240 ampere hour lead lined wooden all type
2—For control—250-volt, 132 ampere hour, glass cell type

MOTOR GENERATOR SETS

For D. C. control battery charging—4-25-kw., 250-volt, shunt wound

HIGH-TENSION TESTING EQUIPMENT

1—Kenetron set	200/50 kv., 25/1 ampere
1—Test transformer	400 kv-a., 25 cycle, 4600/80,000 volts
1—Test transformer regulator	200 kv-a., 25 cycle, 2300/2300 volts
1—Mercury arc rectifier	9000 volt, 6.6 ampere direct current
1—Tracer current motor generator	1000 volt, 500 watts

Discussion

M. S. Sloan: The paper by Messrs. Grady, Lawrence and Tapscott describes the largest single generator unit operating on, and the most recent station of, The New York Edison system. The paper states that while this comparatively new station was started as a 25-cycle station, present plans indicate that future development of The New York Edison system will be at 60 cycles, the initial plan for the station being consistent with the development of The New York Edison Company as it had existed as a separate corporate entity and with its local development program, while the plan to make future extensions at the higher frequency is a logical expression of present conditions. The actual development of the station to date and the future plans in the matter of frequency fit very nicely into the actual and prospective load conditions of the system.

The change of plan in the matter of frequency is one detail of our program of distribution development which started with and was a result of the bringing under unified management and control five companies in the Metropolitan area and serves as an illustration of the engineering and economic advantages which result from logical operative consolidation of properties.

It is scarcely necessary to point out to a body of engineers the considerable expense, both capital and operative, involved in maintaining two frequencies within an area as closely defined as that of New York City.

This economic waste is fundamental and intrinsic and not associated with any question of ownership or control. It is significant, however, that it took substantial identity of ownership and unified control to effectuate unification of frequency.

One measure of the cost of multiple frequencies is found in the fact that 200,000 kw. of frequency conversion equipment had been installed in order to enable the operation of these two frequencies as one system, partially to gain the benefits of diversity, to make reserve capacity more fully available and to enable the partial utilization of the most efficient generating equipment on the system.

Obviously no one would contemplate the establishment or the maintenance of two different frequencies unless there were sound engineering and technical reasons for so doing. Most engineers realize that in generation the advantages of 60 cycle as compared with 25 cycle are very slight while, on the other hand, the utilization advantages of the higher frequency are so great as to constitute almost essential requirements. Certainly this is true in alternating current lighting and measurably true in direct power applications. The reasons then for the original development and continuance of 25-cycle generation lay in its conversion to direct current either for general distribution or for traction systems—I here leave out of consideration the earlier long distance transmissions.

A synchronous converter, then, was for our Metropolitan Area the main reason for extending 25-cycle generation. Recent developments have removed this compelling consideration.

In recent years, perfectly good 60-cycle rotary converters have been developed for both what is commonly known as Edison distribution and the somewhat higher voltage traction use. In addition, the more recent experience with large mercury rectifiers has dispensed with the necessity for synchronous converters at normal city traction voltages and at the voltages used on inter-urban and main line electrification.

Extensive practical experience with the low voltage alternating-current network has demonstrated that in first cost and efficiency it is the ideal system of distribution and that continuity of service and closeness of voltage regulation are assured facts. It offers the most rapid method of expanding the distribution system to meet the growing needs of the consumer and relieves, to the highest degree, the congestion of the city streets.

Utilization development has brought into more general use variable voltage elevator drive thus relieving one of the previously insistent demands for direct-current.

The more modern developments of radio and therapeutic equipment and certain types of domestic refrigerating appliances all have combined within the last half a dozen years to create a positive customer demand for 60 cycle service. For these reasons it has been determined that the development of The New York Edison system shall be by a systematic expansion of 60-cycle, alternating-current, closed network system of distribution.

After exhaustive study by our own engineers we were able to offer to the Board of Transportation of the City of New York, for the subways now approaching completion, 60 cycle service delivered at its various substations under a contract extraordinarily favorable to the city not only in the matter of price but also in the flexibility and liberality of its various provisions as to prompt expansion or cancellation. This could have been done only by utilizing for that service the general distribution system.

The engineers of the Board of Transportation and their consultants made an equally exhaustive and painstaking study which found the use of 60 cycle either through synchronous converters or mercury rectifiers to be entirely feasible on this undertaking which contemplates the use of over 200,000 kw.

These various considerations have demonstrated the necessity and the practicability of a single standard of frequency toward which the development of The New York Edison System must trend. It is obvious that interconnections, whether with immediately neighboring companies or with distant hydroelectric plants, can be accomplished only at the prevalent frequency.

W. S. Gorsuch: I would like to ask whether any special features of feed-water treatment are required for a boiler having a capacity of approximately 1,000,000 lb. of steam per hour?

The reason for adoption of the size of boilers and turbine in the last extension of the plant is of special interest, particularly with regard to the relation of unit size and the features of the electrical distribution system. I would like to know whether the future developments in the electrical system influenced the final decision as to the size of boilers and turbine?

It would be of interest if the authors would describe the method of handling the steam from the steam-driven auxiliaries in the feed-water system.

W. B. Kouwenhoven: 1. Mention is made of the striking reduction in the floor area and cubical contents of the recent addition to the electrical galleries. Will the authors describe the features of design to which they attribute this marked saving in electrical construction, inasmuch as they state in their paper that there are but few special features which are not common to all modern isolated phase galleries, and no immediate economies over previous layout occurred?

2. Would the discussors of the station expect a further high reduction in electrical gallery construction costs by the adoption of 60-cycle units at higher voltage than is used at present with the 25-cycle generators, and what difficulties in the station layout would they expect such an innovation to cause?

C. B. Grady: Answering the questions by Mr. W. S. Gorsuch, (1) The Hall System is used; (2) In our initial installation at East River we purchased the largest 25-cycle turbo generator units which either of the large manufacturers would offer at that time. These were 60,000-kw., single shaft units. The same request was made of the manufacturer at the time of the last installation and the proposition of 160,000-kw. units was accepted at that time. The anticipated developments in the electric distribution system did not influence the capacity of these units as at the time of their purchase there were no anticipated changes in the 25-cycle system; (3) The exhaust steam from all of the station steam driven auxiliaries is discharged into a common header. This header is connected to each second

stage heater in the four stage heating cycle of each of the three main units.

R. H. Tapscott: Referring to questions by Professor W. B. Kouwenhoven, (1) The statement regarding reduction in floor area and cubical contents is on a per kilowatt basis. The paper describes the reduction in number of switches required for the bus ties and feeders as well as the elimination of bus tie reactors. With the largest size generator the number of substation feeders per feeder switch was increased from two to three. The total number of switches, therefore, used for 160,000 kw. was 40, requiring 0.215 sq. ft. of floor area per kw. capacity and the number in the initial installation for 60,000 kw. was 33, occupying 0.48 sq. ft. of floor area as mentioned; (2) Layouts have been made for 60-cycle units both on the basis of distributing at generator voltage and distributing at double generator voltage. At generator voltage the gallery space would be about the same for 60 cycles as for the last unit installed for 25 cycles. At the increased voltage the gallery space would be about the same as for 25 cycles, but additional space would be required in the gallery basement for the installation of step-up transformers. The total building requirement will probably be approximately the same as in the 25-cycle layout.

Present Day Hydro Power Practise in Central Europe

BY A. V. KARPOV[1]

Member, A. I. E. E.

Synopsis.—This paper represents the impressions of a European trip made during the summer of the year 1929 and gives a comparative study of the conditions of European development in so far as they are either of a particular interest or different from the conditions in the United States.

The advance made in Europe in the low head developments is attributed in a large part to the advanced work made in the European hydraulic laboratories and to the cooperation between the laboratory and the manufacturer of hydraulic equipment and power plant designer.

The advances made in the design of the large units of Propeller and Kaplan turbines are discussed.

The low head developments are stressed as the most interesting, and a short description is given of the plants in the region of the upper Rhine and the international interconnection system of this region.

The extensive pumping schemes of this region are briefly described.

An attempt is made to outline the power house design tendencies and the new ideas in protecting the river bed from erosion.

The more interesting work done in the hydraulic laboratories is described.

A short comparison between the mixing and placing of concrete as done in Europe and in the States is given.

* * * * *

PRESENT DAY HYDRO POWER PRACTISE IN CENTRAL EUROPE

An inspection trip through Germany, Switzerland, Italy, and France, was made in the summer of 1929, for the purpose of studying the hydro power practise in Central Europe. During this trip, a number of hydro power plants under construction and in operation, turbine manufacturing plants and hydraulic laboratories were visited, and consultations with many authorities on their respective subjects were arranged.

Impressions of the trip are covered in the following reports:

I. Turbine design.
II. Low head developments.
III. Interconnection and improvements in water utilization.
IV. Pumping problems.
V. Power house design.
VI. Energy destroying.
VII. Hydraulic laboratories.
VIII. Cavitation laboratories.
IX. Concrete Work.

Only developments comparable in size to those in the United States were considered and all discussions are limited to such type of developments.

I. TURBINE DESIGN

The modern turbine design is confined to these four types: Pelton, Francis, propeller, and Kaplan.

The general tendency of the present day European practise is to narrow the field of application of the Francis turbine.

Only a few years ago, the Francis turbine was a very universal type, being used for very low heads, as well as for medium and high heads. Today the propeller and Kaplan turbines are used entirely, instead of Francis turbines, for low head developments. At the same time, the Pelton turbines, by increasing the number of jets and runners, are used for much lower heads than before. That leaves to the Francis turbine a much smaller field, in the medium head developments only.

The curves of Fig. 1 give an approximate idea of the heads and specific speeds for which these types of turbines are used.

In interpreting these curves it is to be kept in mind that for the propeller and Kaplan turbines and for the

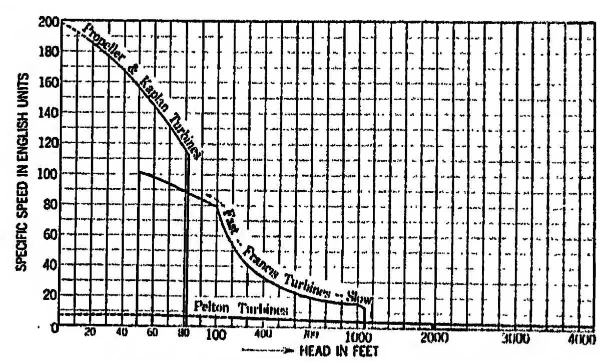

FIG. 1—CURVES OF SPECIFIC SPEED LIMITS FOR SINGLE-RUNNER PROPELLER, KAPLAN, FRANCIS, AND PELTON TURBINES

fast Francis turbines, the curves show approximately the upper limit and for the slow Francis and Pelton turbines approximately the lower limit of specific speeds for a given head.

Propeller and Kaplan Turbines. The most interesting of the present day European designs are the propeller and Kaplan turbines. Strictly speaking, both of these types are propeller turbines, the principal difference between them and the Francis type of turbine being that the water is guided by the stationary part of the turbine in such a way that the water flow becomes axial before the water column strikes the runner blades, (Fig. 2).

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

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The principal difference between the propeller and Kaplan turbines lies in the adjusting arrangement of the runner blades of the Kaplan turbine. The runner blades of a propeller turbine are solidly connected to the hub and the turbine shaft, and cannot be adjusted. The runner blades of a Kaplan turbine can be adjusted for different operating conditions by means of a special mechanism built into the hub of the runner, (Fig. 2).

No particular limitations apply to the size, shape, and number of runner blades of a propeller turbine. As for the Kaplan turbine, the size and shape of the runner blades are such as to avoid any mechanical interference among adjoining blades and form proper hydraulic channels for the passing water; moreover, the number of blades must be kept low so that the adjusting mechanism is simple and small enough to be placed in the proper sized runner hub.

The main advantage of the propeller and Kaplan turbines is the high specific speed for which they can be built, which makes possible a considerable saving in the cost of the electrical equipment.

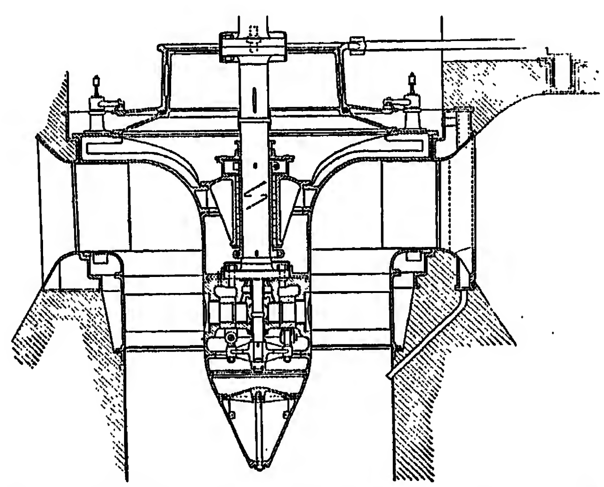

Fig. 2—Sectional Elevation of a Kaplan Turbine

The reduced space necessary for the units results in appreciable savings in the cost of the power house structure.

Also, better efficiencies can be obtained and, a matter of importance for low head developments, the efficiency will be influenced less by the variations of head.

The advantages of these types of turbines are such that at present up to the heads to which they can be safely built, they replace the Francis turbines entirely.

Cavitation. The most important factor that at present excludes the use of propeller and Kaplan turbines for heads above about 80 ft. is the cavitation. The cavitation problem became of such importance in the propeller and Kaplan turbine design that special cavitation laboratories were built and a thorough study of this problem is going ahead in many places. This study and the laboratory work cleared to a certain extent this rather obscure problem and the results of these studies are applied today not only to propeller and Kaplan turbines, but to Francis turbines as well.

Cavitation occurs when the pressure drops in some parts of the turbine so that it is lower than the evaporation point corresponding to the water temperature.

The phenomenon of cavitation consists in the formation of bubbles of vapor supplemented by air which has been in solution in the water. These bubbles, which are formed on the surface of the runner in the low-pressure areas, cause the drop of efficiency, destruction of the runner material, known as "pitting" or "corrosion," and runner vibrations.

It seems that any roughness of the material, visible and invisible cracks, and even changes in the structure of the material due to concentrated internal stresses, may produce or increase existing cavitation.

Cavitation, even at a very small degree, will start the destruction of the material, which will intensify the cavitation, bringing forth further destruction, as well as the decrease of the efficiency and the increase of vibrations. In a properly designed turbine no cavitation must occur at all.

In the old fashioned Francis turbines, the water was smoothly guided, and the pressure drop from guiding vanes, where the water entered the turbine, to the draft tube was very gradual. The point of highest pressure corresponded to the point where the water entered the turbine and the pressure decreased until the lowest pressure was reached at the point where the water left the runner and entered the draft tube. To prevent cavitation in such design, it was only necessary to have the pressure at the draft tube entrance higher than the evaporation pressure.

The pressure drop at the draft tube entrance depends very closely on the draft tube head and efficiency, and on the velocity at which the water enters the draft tube. If these conditions were properly chosen, the cavitation danger was prevented for such turbine design.

In the more advanced Francis turbine designs, and particularly in the fast running Francis turbines which were first introduced in the United States, the conditions are different. The water is rather forced and not smoothly guided as in the old designs. Under these conditions the pressure does not change gradually from the wicket gates to the draft tube and the point of lowest pressure may be transferred from the draft tube entrance to some point on the runner. In such designs, it is usually possible by proper change of the shape of the runner and by decrease of the draft tube head to eliminate the cavitation danger.

Conditions are different in the propeller and Kaplan turbines, where the point of lowest pressure is always above the draft tube entrance, being located somewhere on the runner blade.

Fig. 3 shows the characteristic pressure distribution on the surface of a Kaplan turbine runner, the section being taken at the Line *C–C*. The figures along the surface of the blade and the pressure curves are to be considered as coefficients only. The actual pressures

depend on the water velocity and draft tube head. For this particular shape of the Kaplan runner, the point K represents the point of the lowest pressure. The pressure at this point is always lower than at the draft tube entrance and will decrease rapidly with the increase of the specific speed.

In a turbine of that type, a sufficient pressure at the draft tube entrance is no assurance whatsoever against cavitation troubles.

The propeller and Kaplan turbines, with the increase of the water head, very soon approach the limit at which even a zero draft tube head will be insufficient to prevent cavitation. Today about 80 ft. will represent for these turbines the upper limit of the water head for zero draft tube head. By lowering the runner below the low water elevation, an increase of the water head could be obtained, but probably at high cost only.

Another method is now under consideration. It

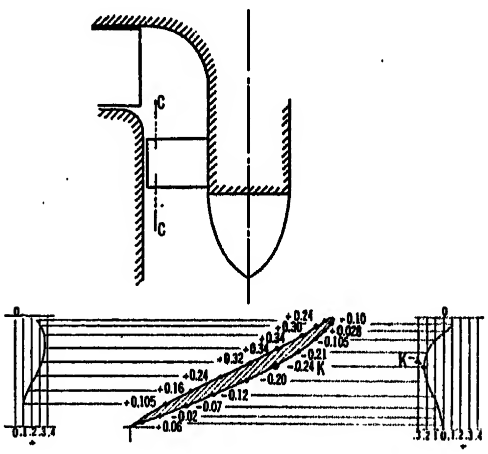

FIG. 3—PRESSURE DISTRIBUTION AT THE SURFACE OF A KAPLAN TURBINE RUNNER BLADE

consists of dividing up the head and using two turbines in series, so as to have the first turbine working against the total pressure under which the water enters the second turbine.

By the very nature of the modern design, the turbine must be kept very close to the limits at which cavitation will occur, since the economical design requires a high specific speed turbine that is set reasonably high, but at the same time free from cavitation. This can be accomplished only if the proper design is supported by a very careful fabrication to prevent the cavitation danger.

To meet these conditions, the manufacture of such turbines is at a very high standard in the leading European turbine manufacturing plants. The tendency is to have all the parts of the turbine which come in contact with moving water perfectly machined. This tendency, together with the experience that was gained in the Kaplan turbine design, brought out the up-to-date designs of the large size propeller turbines in which the runners are made of a separate hub and blades that are bolted together. Such a design not only makes possible a better fabrication and removes the internal stresses unavoidable in large steel castings, but increases considerably the size of runners that can be shipped by railroad, by shipping the runner in separate parts which are bolted together at the power house.

There are special machines for machining Kaplan and propeller runner blades, mostly built as copying machines, the surface of the blade being machined to represent an exact but increased copy of a small model of the runner blade. The erection of such machines, of very large size, was in progress at two leading European plants during the past summer.

Cavitation studies were made mainly on account of the propeller and Kaplan turbines. These studies at the same time are beneficial for the Francis turbines. At one of the leading plants that possesses a cavitation laboratory, the up-to-date practise is to test models of new Francis turbines, as well as propeller and Kaplan turbines, and to determine the limiting conditions at which the cavitation starts. The actual operation conditions are chosen according to the results of these tests.

Efficiency of propeller and Kaplan Turbines. The improvement in the design and efficiency of the propeller and Kaplan turbines presents some interesting features.

Considering the high velocity of the water when it strikes the runner blades and in order to keep down the friction losses, the original Kaplan turbines were built with only a few small runner blades. Since at that time the idea of having the runner blades adjustable had not been applied, these original designs actually were a particular kind of propeller turbine. This arrangement gave satisfactory results for certain loadings and a very rapid decrease of the efficiency by decreased or increased loadings. The water coming down in a propeller turbine, particularly with a runner which has only a few small blades, is not guided in any way, and only for certain loading conditions corresponding to the shape and angle of the runner blades, fairly good efficiency can be obtained. These are the conditions of low eddy losses, owing to a fairly uniform and undisturbed flow of the water through the whole turbine, including the entrance guiding and regulating vanes, turbine runner, and draft tube. Changes in the loading results in an increase of the non-uniformity of the flow, rapid increase of the eddy losses, and a corresponding rapid decrease of the efficiency.

Tests proved at the early stages of the development that a rather large sized hub is necessary for undisturbed flow and high efficiencies.

Making the blades adjustable and locating the adjusting mechanism in the hub resulted in the ingenious present day Kaplan turbine design with its

very flat efficiency curve on a wide range of loadings.

It is natural that in the flat range of the efficiency curve, the maximum efficiency that corresponds to the lowest eddy losses, falls somewhere in the middle part of the efficiency curve.

In a propeller turbine, the number of blades can be increased and the blades can be extended so that the water will be partly guided. This will increase the friction losses, but may decrease the eddy losses. With

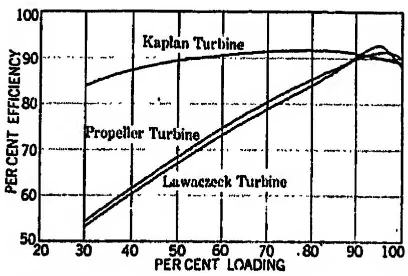

Fig. 4—Comparative Efficiency Curves of Kaplan, Propeller and Lawaczeck Turbines at Varying Loads

the increase of the size of a turbine, the eddy losses grow more rapidly than the friction losses and for large turbines, the maximum efficiency of a propeller turbine can be greater than the maximum efficiency of a Kaplan turbine. Under certain conditions, the further extension of the runner blades that will afford better guidance for the water can decrease the eddy losses so considerably that a still better efficiency can be obtained.

The Lawaczeck turbine is built on this principle and so far as the maximum efficiency is concerned, the results of efficiency tests made on the Lawaczeck turbines in Lilla Edet, Norway, are unsurpassed by any turbine of similar size.

The decrease of efficiency for changed loadings is very rapid in any type of propeller turbine, although, depending upon the design, it can be less rapid than in the original designs of Kaplan turbines with a few small non-adjustable blades. But the point of maximum efficiency of a properly designed propeller turbine will be very close to the maximum loading as against the Kaplan turbine where this point will move over to the middle part of the efficiency curve.

Fig. 4 gives approximate comparative efficiency curves for Kaplan, propeller, and Lawaczeck turbines, of about 10,000 hp., which confirm these points.

Another interesting result of the propeller turbine development and the extensive efficiency tests made in connection with this development, is the proper recognition of the influence that the outer ring of a turbine runner has on the efficiency. A large part of friction losses is due to the presence of this ring, which moves at right angle to the direction of the movement of the water.

In propeller and Kaplan turbines, this ring is entirely eliminated and the tendency is to eliminate such rings even in the big Francis turbines.

Fig. 5 shows a large runner built up from separate pieces bolted together, without the outside ring. This runner is designed to substitute a more conventional low head Francis runner with an outside ring and shows how far the European manufacturers are willing to go in this direction.

Hunting of propeller and Kaplan Turbines. A very unfavorable peculiarity of the first large size Kaplan and propeller turbines was their unsteadiness and the tendency to hunt. Tests indicated that this tendency is due to the irregularity of the water flow in the draft tube that increased with the increase of the size of the turbine, the shortening of the draft tube, and the decrease of the radius of the draft tube elbow. A very successful cure of this trouble was found by building a partition or baffle in the draft tube, starting close to the runner and following the axis of the draft tube as indicated in Figs. 12 and 17. This partition arrangement not only decreased the hunting tendency very considerably, but at the same time increased the efficiency, particularly at partial loadings.

The results obtained with these partitions encouraged future research in this direction and different partitions in the draft tubes and in the scroll cases were tested. The tests proved conclusively that vertical partitions properly built into the draft tube below the elbow and in the scroll case, not only do not show any bad influence, but for large size turbines even

Fig. 5—Large Sized Turbine Runner Without Outer Ring

improve the behavior of the turbine. This proved to be of importance in solving structural problems in building power houses for large propeller and Kaplan turbines. The vertical partitions in such turbines are built out as piers to support the power house structure.

Draft Tube Shape. Due to the fact that in the low head developments the efficiency of the draft tube is much more responsible for the over-all efficiency of the installation than in the higher head developments, a large amount of laboratory research

is done in this direction, with rather surprising results. The old fashioned elbow draft tube properly shaped and somewhat extended in horizontal direction seems to be superior for this kind of developments to the many fancy shapes which were advocated so much in the past. Practically all the latest larger low head developments that showed remarkably high efficiencies, as well as the new designs, are made with an elbow type draft tube.

Inclined Wicket Gates. The latest improvement in propeller and Kaplan turbine design is the inclined arrangement of the wicket gates (Fig. 6). This arrangement not only gives a considerable saving in the over-all sizes of the turbine, but in some cases improves the efficiency. The same inclined arrangement of wicket gates can be applied to fast running low head Francis turbines.

Vertical and Horizontal Shaft Turbines. The introduction of propeller and Kaplan turbines increased very much the tendency for vertical shaft turbines, as far as Francis, propeller, and Kaplan turbines are concerned. The Pelton turbines are not influenced by this development and still have horizontal shafts.

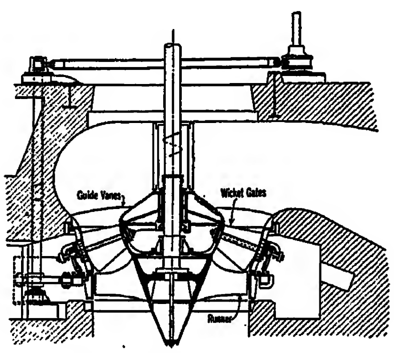

FIG. 6—INCLINED WICKET GATES ARRANGEMENT

The trend that started quite a number of years ago to use vertical shaft turbines for high and medium head Francis turbines, was not very pronounced in the low head developments. On the contrary, the low head developments that were designed only a few years ago with fast running Francis turbines, had a decided trend for horizontal shaft turbines. The main reason was the possibility of using a number of turbines on one shaft, which allowed an increase in the specific speed of the turbines. At the same time, if couplings were provided on the shaft, the number of turbines in operation could be made to correspond to the amount of water available and in this way to operate the Francis turbines at favorable efficiency.

The horizontal shaft multiple turbine unit recently installed in the power house "Pfrombach" in Bavaria with eight horizontal Francis turbines, one single-phase and one three-phase generator on the ends and an electrical regulating set, represents an extreme step in this direction.

This design was prompted by an unwillingness to use propeller or Kaplan turbines and by the peculiarity of loading of the power house, which has to supply single-phase $16\frac{2}{3}$ cycles and three-phase 50 cycles alternating current. If this power house were redesigned today, vertical shaft propeller and Kaplan turbines and a rotating single-phase—three-phase converter would probably better solve the same problem.

Replacement of Older Turbine Designs. A remarkable picture of the advantages of a propeller or Kaplan turbine as compared with the older designs of turbines for low heads can be seen in the recently made replacements of multiple runner vertical shaft turbines, by a single runner propeller or Kaplan turbine. These replacements were made with only minor changes in the masonry and with considerable increase of the maximum capacity. By using a Kaplan turbine, the efficiency at lower loadings, due to the flat efficiency curve of the turbine, is still higher than the efficiency of the original turbine. The saving in space by use of the inclined arrangement of the wicket gates is particularly adaptable for such replacements.

Regulation of propeller and Kaplan Turbines. In order to make the amount of water entering a propeller turbine correspond with the load conditions, the same process is used as in Francis turbines. The water entering through the scroll case passes first the fixed guiding vanes and then the movable regulation vanes or wicket gates. The governor of the turbine actuates the servo motors which move the wicket gates, causing the increase or decrease of the amount of water passing through the turbine.

An additional regulation, consisting in turning the runner blades, corresponding to the change of loading conditions, is necessary for the Kaplan turbines, a fact that has brought out quite a number of new problems. A poor result, so far as the efficiency is concerned, is obtained from the separate regulation of either the wicket gates or the runner blades.

For proper regulation of the turbine, the angle of the runner blades has to correspond to the position of the wicket gates. These corresponding positions are influenced by the variations of the head.

The regulation can be accomplished either by simultaneous operation of the wicket gates and runner blades, or by making the regulation in two stages: the first stage or the main regulation by operating of the wicket gates, and the second or adjusting operation by operating of the runner blades so as to bring them to the proper position. It is possible to make the main regulation by operating the runner blades and the adjusting by operating of the wicket gates.

In all present designs, the main regulation is accomplished by the governor acting upon servo motors and changing the position of the wicket gates so as to keep the number of revolutions constant at the different

loadings. The subsequent adjustment is made by the operation of the runner blades.

In the earlier designs of Kaplan turbines the actuating mechanism for the adjustment of the runner blades was regulated from time to time by hand. In the up-to-date designs, it is operated automatically by the governor.

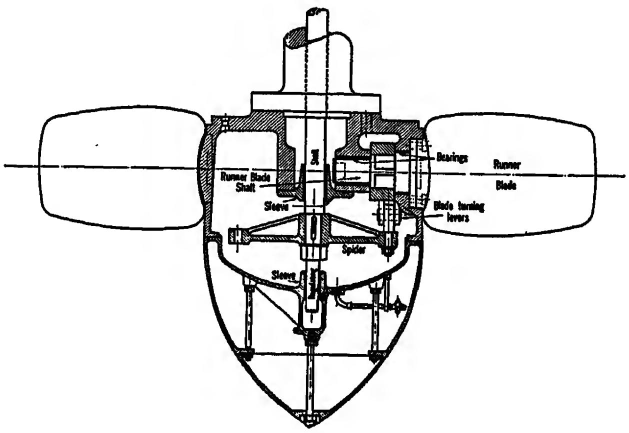

Fig. 7—Cross Section Through the Hub of a Kaplan Turbine Runner

The cross section of a recent design of a Kaplan turbine runner is shown on Fig. 7. The runner blades have an extended shaft end which is supported on two bearings. Between these bearings a lever arm is fastened to the shaft and is connected by means of rods

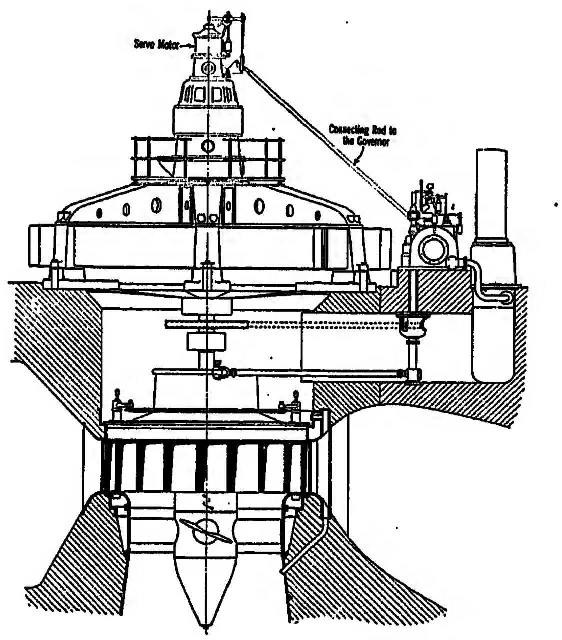

Fig. 8—Elevation of a Kaplan Turbine with the Servo Motor Above the Generator

to a spider. By moving the spider up and down, the blades of the runner are turned in one or in the other direction. The spider is solidly connected to a regulating shaft which can move up and down in the hollow shaft of the turbine. The regulating shaft is guided by two vertical sleeves, one above and one below the spider. The whole arrangement is oil tight and is kept filled with oil. The regulating shaft is moved by means of a compressed oil servo motor.

In the smaller Kaplan turbines, the servo motor that moves the regulating shaft is located above the generator.

Fig. 8 shows a general view of such a turbine and Fig. 9 the details of the servo motor. In this design the regulating shaft is continued through the hollow generator shaft and is connected with the piston of the servo motor. An indicating rod that is connected with the top of the regulating shaft is extended above the servo motor and connected by means of a system of levers with the governor and a slide valve. The angle of the runner blades is indicated by the position of the indicating rod, the movement of which is transferred to a special designed governor. The governor is arranged in such a way that if the angle of the runner blades does not correspond to the position of the wicket gates,

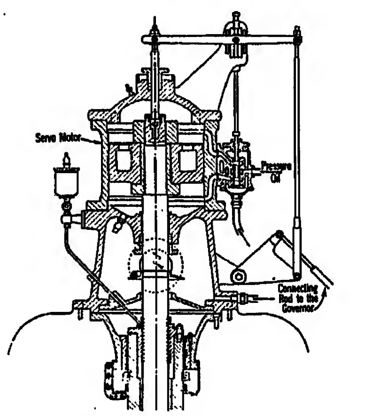

Fig. 9—Details of the Kaplan Turbine Arrangement of the Servo Motor Above the Generator

the sliding valve is actuated and the servo motor moves the regulating shaft until the necessary correspondence between the two factors has been accomplished. In order not to move the runner-blades at every slight movement of the wicket gates, the runner-blades governor is made so that it has a certain time lag with reference to the governor that actuates the wicket gates. Owing to this time lag the runner blades adjustment follows only the major regulating movement of the wicket gates and does not follow the minor swings of the wicket gate regulating mechanism. This regulating arrangement has a number of following drawbacks on account of which it is not very well suited for large size turbines:

1. The servo motor piston rotates in a stationary cylinder.

2. The long regulating shaft represents a heavy weight that is to be moved by each adjustment.

3. The hollow generator shaft is to be very heavy in order to accommodate the regulating shaft.

For large Kaplan turbines, the latest design shown

in Fig. 10 with the servo motor located between the turbine and generator shaft is expected to be a considerable improvement. In this design the regulating shaft is much shorter and since the piston of the servo motor rotates together with the cylinder no relative rotation movement between the piston and cylinder occurs. The hollow generator shaft has to accommodate only two oil pressure pipes that convey oil to the servo motor. These pipes rotate together with the generator shaft. The central pipe is solidly connected to the regulating shaft, and the indicating rod, connected to this pipe above the generator, indicates the angle of the runner blades, and this indication is transferred to the governor by means of a lever system. The rotating oil pressure pipes have a cap arrangement above the generator that permits the pressure oil to enter from stationary pipes to the rotating pipes. The servo motor is actuated by a governor that changes

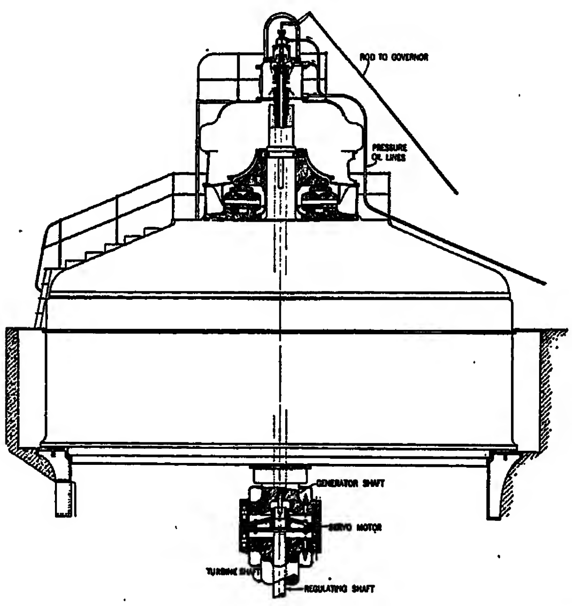

Fig. 10—Details of the Kaplan Turbine Arrangement of the Servo Motor Between the Turbine and Generator Shafts

the amount of pressure oil below and above the piston of the servo motor until an adjustment of the runner blades corresponding to the position of the wicket gates takes part.

All these arrangements do not take into consideration the influence of the different water heads and have to be set for some mean water head.

In general, it seems that the regulation problem of Kaplan turbines is still in an embryonic stage. Quite a number of improvements are possible to get the proper synchronization of both regulating mechanisms on a predetermined basis for different operating conditions.

In keeping in line with the general tendencies in governor design, the governors on the latest Kaplan and propeller turbine designs are mostly electrically driven instead of by a belt or a gear drive.

II. Low Head Developments

Probably the most interesting of present day European developments are those for less than 80 ft. head.

The introduction and rapid increase in size of the propeller and Kaplan turbines changed considerably the economical aspects of these developments and made possible plants that a few years ago were considered uneconomical.

The upper part of the Rhine River, between Lake Constance and Strasbourg, gives an interesting picture of the new low head possibilities.

There are under construction two large plants, the Ryborg-Schworstadt plant located on the border line between Germany and Switzerland close to Rhinfelden, and the Kembs plant located on the French side of the Rhine close to Mulhouse.*

The turbine units in both of these plants are the largest ever built so far as the physical dimensions and the amount of water handled by each unit are concerned.

An idea of the economical advantage of using large sized Kaplan turbines for low heads can be gained by comparison of the Laufenburg and the Ryborg-Schworstadt plant. Both plants are very similar in size and capacity, the Laufenburg plant being located a short distance above the Ryborg-Schworstadt plant. The Laufenburg plant is of an older design and was built before the war. It contains a large number of Francis turbines.

Taking into consideration the differences in the prewar and present day prices, the cost of an installed kilowatt in Ryborg-Schworstadt is estimated to be 30 per cent lower than in Laufenburg.

Here are the comparative data of the Ryborg-Schworstadt and Kembs plants:

Power House..........	Ryborg-Schworstadt	Kembs
Head in feet..........	35	54
Kind of turbines......	Kaplan	Propeller
Number of units......	4	5
Capacity of unit in horsepower	35,000	36,000
Installed capacity in horsepower	140,000	180,000
Quantity of water handled by each unit in cu. ft. per sec.......	10,500	6,800
Number of revolutions per minute..........	75	94
Diameter of the runner in feet.............	23.0	18.4

Ryborg-Schworstadt Development. The Ryborg-Schworstadt plant is located in a dam built across the Rhine. The general arrangement is shown in Fig. 11.

The cross section through a Kaplan turbine is shown on Fig. 12.

The water enters the concrete scroll case of each

*The author briefly described these plants in *Power* of April 1, 1930.

turbine through three passages formed between concrete piers, and passes through guiding vanes and wicket gates into the runner. After leaving the runner, the water enters the draft tube which has a steadying partition and a supporting pier. The piers in the in-

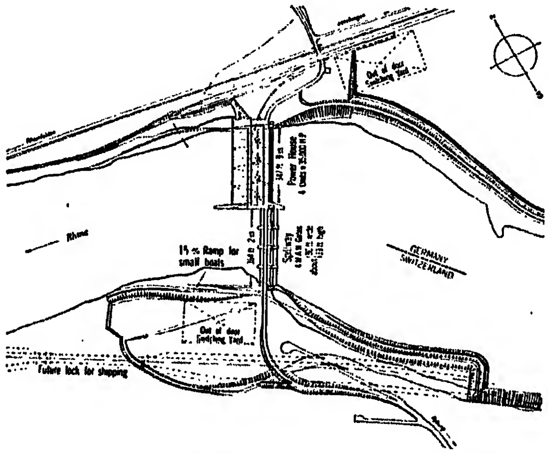

FIG. 11—RYBORG-SCHWORSTADT POWER PLANT. GENERAL PLAN

take and draft tube are used to support beams and slabs and carry the power house load.

The thrust bearing load is carried down in solid masonry partly by the guiding vanes of the turbine.

The concrete fill indicated by lighter cross sectioning is used only at a part of the power house where the solid gravel foundation of the river bed was washed away and the soft natural fill had to be replaced by concrete.

The rest of the power house is built as shown by the heavier cross sectioning.

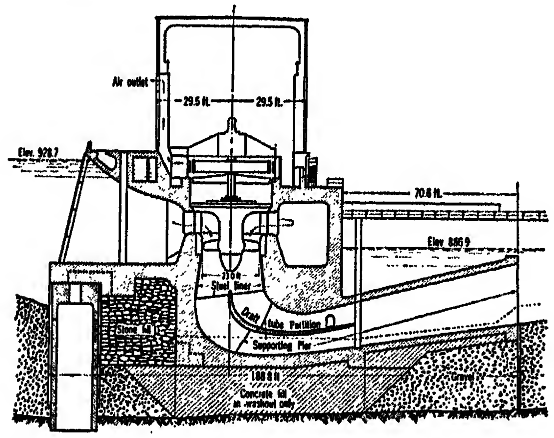

FIG. 12—RYBORG-SCHWORSTADT POWER PLANT. CROSS SECTION AT THE CENTER LINE OF A UNIT

The unusual feature of this design is the absence of head gates in front of the turbine.

In normal operation the only way to stop the turbine is to close the wicket gates and by applying brakes to bring the runner to a stop in spite of possible leakage.

For emergency repair work, stop log provisions are made.

Another interesting feature of this plant is the main gates in the dam.

From the maximum total flow of the Rhine River that can be as high as 200,000 cu. ft. per sec., about 35,000 cu. ft. per sec. can be discharged through the power house and the rest is taken care of by four gates. These gates have a clear opening of about 80 ft. wide by 39 ft. high and are of the M. A. N. (Maschinenfabrik Augsburg Nurnberg) design.

The section through such a gate and the plan view of it are shown on Fig. 13.

The gate consists of a separate upper and lower part. The lower part of the gate is stiff enough to carry the water pressure, but the upper part of the gate has a stiffening beam at the top only; the bottom is flexible. The water presses the flexible part of the gate against the stiff lower part. A rubber strap fixed to

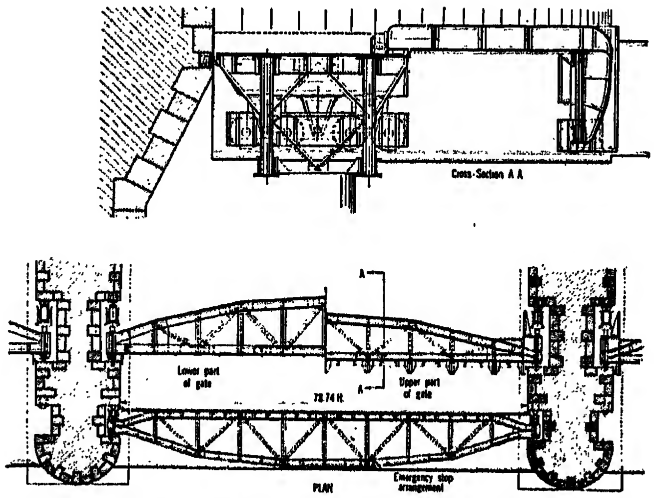

FIG. 13—RYBORG-SCHWORSTADT POWER PLANT. M. A. N. GATES

the lower part of the gate and sliding against the upper part insures a water tight joint.

The water tightness at the bottom is assured by a wooden beam pressing against a steel plate sill. At the sides of the gates, the tightness is assured by flexible steel plates which are pressed against guiding structural steel members.

The raising and lowering of the gates is done by an overhead electrically operated crane and the gates are operated by lowering the upper part of the gate or by raising the lower part of it, and finally by lifting the whole gate out of the water. This arrangement gives a perfect water control and at the same time, by letting the water flow above the gate or below it, a removal of all floating rubbish, as well as of the sand and gravel accumulated at the bottom of the gates, is possible.

Since at this size of the opening no stop logs can be used, the emergency closing of the gate is accomplished by lowering a number of steel frames handled by an auxiliary crane in the specially provided slots. These steel frames are covered with sheet metal and the water

tightness at the bottom, between the individual frames and at the sides is assured by wooden beams, which are permanently connected to the steel frames.

This design is becoming very popular for large sized

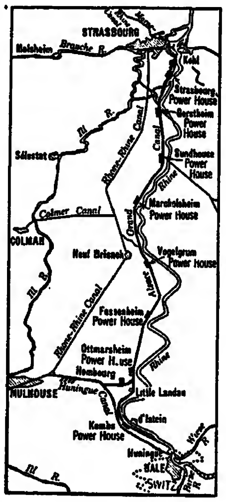

Fig. 14—Kembs Power Plant. Plan of the Canal

gates and designs are considered for sizes even larger than the Ryborg-Schworstadt gates.

Kembs Development. The Kembs plant is the largest and the first power plant out of a series of eight plants

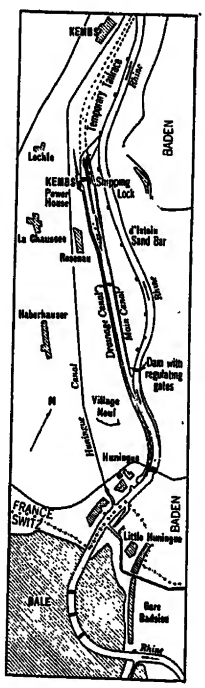

Fig. 15—Kembs Power Plant. Location Plan

proposed on the shipping canal, Grand Canal d'Alsace (Fig. 14) which are to be built between Basel and Strasbourg as part of the German reparation payments. Fig. 15 shows the location of the Kembs plant and the temporary tail race.

The plan (Fig. 16) and the cross section (Fig. 17) of the Kembs power house shows a design quite different from Ryborg-Schworstadt.

A customary design of a dam with the necessary gates and spillways and the power house proper would require a much larger widening of the canal at the power plant.

The present day design was worked out, taking ad-

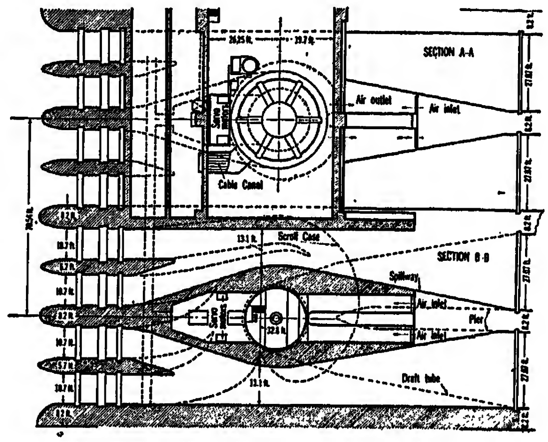

Fig. 16—Kembs Power Plant. Plan of Power House

vantage of the fact that the main regulating gates are located in the dam at the Rhine River and that the amount of water flowing through the canal is limited.

Corresponding to each unit of the power house, there are eight intakes which are opened and closed by head gates. Four of these intakes are on a lower elevation and lead the water to the concrete scroll case of the turbine. The four intakes at the higher elevation lead

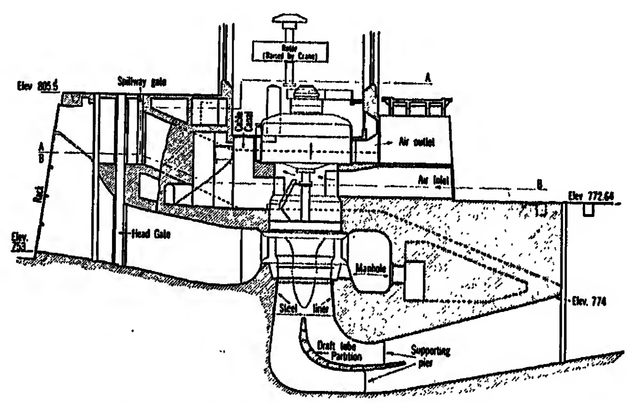

Fig. 17—Kembs Power Plant. Cross Sections at the Center Line of a Unit

the water below the main power house floor to the overflow spillway which is indicated in Fig. 16 with dotted lines.

The turbine is completely separated from the spillway by the central concrete pier, as shown on section *B-B* (Fig. 16). By closing the lower intake gates and opening the upper intake gates of a unit, the water will flow at the outsides of the central pier and any repair

work that has to be done on the unit can be done without any interference from overflow water by lifting the rotor of the generator and by subsequent lifting of the turbine runner.

The outlet of the spillway and the draft tube are brought together and the spillway will be shaped in such a way as to improve the output of the turbine in times of high water and decreased heads.

The supporting piers at the intakes and draft tube and the draft tube partition are provided in a way somewhat similar to the Ryborg-Schworstadt design.

Provisions for emergency stop logs are made in front of the intakes and at the end of the draft tubes and spillways.

Both the Ryborg-Schworstadt and the Kembs developments leave the impression of being very thorough and careful designs which can be brought out only by a very close cooperation between the turbine and power house designers and by an effective support of proper hydraulic laboratories.

Propeller or Kaplan Turbines. For present day low head developments, there are three possible choices of turbines:

1. Propeller turbines only.
2. Kaplan turbines only.
3. Propeller and Kaplan turbines.

The Kembs development is an example of the first choice, and the Ryborg-Schworstadt the second. The Lilla Edet power plant in Norway with two propellers (Lawaczeck) and one Kaplan turbine is a good example of the third choice.

The propeller turbine is simpler, cheaper, and can be designed to have at a loading close to 100 per cent, a very high efficiency, but at smaller loadings the efficiency will drop off very rapidly.

The Kaplan turbine is complicated, more expensive and, having a flat efficiency curve at a large range, will generally have a slightly lower maximum efficiency than the propeller turbine.

A good illustration of the difference between the efficiencies of a Kaplan and a propeller turbine is the fact that for units of about 40,000 hp., the amount of water that is necessary to turn idle a propeller turbine will deliver about 10,000 hp. in a Kaplan turbine. At conditions approaching full load, the amount of water that will deliver about 39,000 hp. in a propeller turbine will deliver less than 38,000 hp. in a Kaplan turbine. These differences in the two types of turbines in connection with local conditions will govern the proper choice.

In the Kembs power house, with a larger number of units and gradual changes in the amount of water, it was thought that by varying the number of units in operation it will be possible to have them work most of the time in the favorable range of the efficiency curve and the simpler and less expensive propeller turbines were decided upon.

In Ryborg-Schworstadt each unit is owned by a separate concern and, it is expected to work all four units all the time and change the loading of each unit according to the available water flow.

Under these conditions it was thought advisable to use the more complicated and more expensive Kaplan turbines for all four units. At the same time these conditions made it possible to eliminate the head gates, and in this way to compensate partly for the higher cost of the Kaplan turbines.

The Lilla Edet power house probably represents the average conditions better. There the idea is to run the propeller units always at the point of maximum efficiency and to have all the regulation taken care of by the Kaplan unit.

A good insurance against changes of the conditions assumed at the original design can be had by building the propeller turbines in such a way that a Kaplan runner can be inserted and the turbine run as a Kaplan turbine or vice versa.

III. Interconnection and Improvements in Water Utilization

Most of the European power plants are connected to some distribution system and carry, partly at least, public utility load with its daily and seasonal variations.

The steam power plants of such systems take care of the deficiency in water power, but at the same time far reaching provisions are made for the best possible utilization of the available water flow and of adjustments to the variable load conditions.

The extensive use of water pumping schemes and the connection with chemical plants are the most important and interesting means of regulation.

The region of the upper Rhine shows the highest stage of development. Here the Rhine power plants, the power plants of Southern and Western Germany, Austria, and Switzerland, and through Switzerland, the French plants, form one of the largest international interconnected systems of the world.

The hydro plants of the upper Rhine have practically no storage and have to utilize the available water flow or waste the water. Due to the regulating influence of Lake Constance, the daily variation in water flow is small, but the seasonal variations are rather large. Since most of the water comes from the Alps, the largest flows occur in summer time and a scarcity of water and power is most noticeable in the winter time.

The whole region is so operated as to avoid any waste of water in plants having no storage capacity. Not only the seasonal or daily load variations are taken care of, but even the mid-day dropping off of the load is provided for.

This is achieved mainly by:

1. Regulating the load of steam plants.
2. Regulating the load or shutting down hydro plants having available storage capacity.
3. Starting and stopping water pumping in the

higher reservoirs on the German and Swiss sides of the Rhine.

4. Regulating the load of chemical plants.

The pumping problems are to be discussed separately.

So far as the chemical plants are concerned, let it be suffice to mention that in some cases they are directly owned by the power plant and some of them can take on or drop off as high as 20,000 kw. at one-half hour notice.

An interesting detail of the recent German practise toward better water utilization is the use of ground water in localities where such water is abundant. Depending upon the local conditions, a certain time lag exists between the maximum river flow and maximum ground water flow, as well as between the minimum river flow and the minimum ground water flow. Due to this time lag, even a comparatively small amount of ground water can have a good regulating effect.

IV. Pumping Problems

Quite a number of possibilities for regulating and improving the output of power plants can be obtained by including a pumping scheme in the development.

In the past, pumping was not used to a large extent, but its use is increasing rapidly and the probabilities are that in the future it will be used very extensively.

The over-all efficiency of any pumping scheme seldom can exceed 60 per cent. On account of this low efficiency, the pumping schemes that utilize the waste water in most cases are the ones that show the best economical advantages. The schemes in which water that could be directly utilized is pumped into reservoirs will be justified only if the difference in price is large enough between the power delivered from the artificially stored water and the power that could be delivered by direct prime mover generation.

In order to get the full benefit of pumping, the pumping installation ought to be part of a large interconnected system, where the combinations of different kinds of high and low head plants with and without storage capacity create conditions that will make pumping advantageous.

The different pumping schemes actually used and proposed can be subdivided into three types and will be illustrated by a very brief description of developments that fit into each of these types. The division is as follows:

1. For daily regulation mainly. Murg and Schwarzenbach development near Forbach, Baden.

2. For seasonal regulation mainly. Waeggital development near Zurich, Switzerland.

3. For increase of the output of a power plant at high water and low water seasons. Proposed by Dr. Eng. Lawaczeck for plants with extremely variable head.

Both the Murg and Schwarzenbach and the Waeggital developments are parts of the upper Rhine interconnection systems and are located in the hills on the German and Swiss sides of the Rhine respectively.

Murg and Schwarzenbach Development. This development has two storage reservoirs located at different elevations. The higher reservoir delivers the water to the power house under an effective head of 1180 ft., and the lower reservoir under 460 ft.

The power house has correspondingly two sets of turbines and the water is led to the power house by two sets of penstocks.

The pumps are coupled to the horizontal shafts of the high head turbines and are driven electrically, running the main generator as a motor. The pipe connections are made in such a way that the pumps take the low head reservoir water through the low head penstocks and pump it through the high head penstocks into the high head reservoir.

At peak load conditions, the high as well as the low head units are delivering energy and the pumps are disconnected. At times of moderate energy demand only the low head units deliver energy. At times when the demand is smaller than the energy that the system can supply, the pumps are connected with the high head units and pump the water from the lower to the higher reservoir, drawing the electrical energy from the system.

The whole operation is so regulated that, besides the daily load variations, a seasonable load variation is taken care of by filling up the higher reservoir in times of high water flows and drawing it down in times of low water flows.

Waeggital Development. In this development the total maximum head is 1500 ft. The reservoir is an artificial lake of about 5.2 billion cubic feet capacity. The head is utilized in two steps.

The first step is formed by the power house "Rempen" with a maximum head of about 850 ft. By means of a tunnel and a set of penstocks, the water is led from the lake to the Rempen power house, after which it passes through the turbines into a tail race that is formed by a small regulating pond, which also has an appreciable natural inflow.

The second step is formed by the power house "Siebnen" with a maximum head of about 650 ft. The water is led from the Rempen power house regulating pond by a set of pipes and penstocks to the Siebnen power house and discharged into the river.

The pumping equipment is located in the Rempen power house and consists of a set of independent electrically driven pumps. Each pump corresponds to a main turbine generator unit and the pipe connections are made so that each pump takes the water from the Rempen regulating pond and pumps it through the penstock of the corresponding turbine into the lake.

The main purpose of this development is to increase the supply of power in winter time when the demand is large and the amount of water falls off.

The two plants are operated together in winter only

During the summer months the Siebnen plant is shut down entirely so far as delivery of power is concerned. The electrical generators of this plant are run as synchronous converters to improve the electrical conditions of the system.

The Rempen plant at peak load delivers power to the system; the rest of the time it pumps back the water which was used in peak load hours and pumps all the natural inflow of the Rempen regulating pond into the Waeggital lake.

In this way during the summer the lake elevation is raised, the lake receiving besides its natural inflow all the inflow of the Rempen regulating pond.

In winter at times of heavy load demand both power houses are delivering power and at times of lighter power demand a part of the water is pumped from Rempen pond back into the lake.

Lawaczeck Scheme for Developments with Very Variable Heads. This scheme was proposed recently for rivers in which, in times of high flow, the amount of water increases considerably and the tail race elevation rises close to the intake elevation.

For such developments it is proposed to install small reservoirs which may be concrete reservoirs at an elevation higher than the highest river elevation. The water is to be pumped into such reservoirs when the river rises; that will create an additional water head and the turbines shall be run with water under this artificial head. In connection with this scheme special turbine pumps are proposed.

Types of Pumps. The pumps that are in actual use or that are proposed for different schemes can be divided as follows:

Independent motor driven pumps.

Pumps that are connected with the turbine generator units.

Special Lawaczeck pumps.

Independent Motor Driven Pumps. Since, for the motor driven pump, the number of revolutions of the motor can be chosen so as to be favorable to the pump requirements, this kind of pump has certain advantages that are particularly noticeable if the pumping is to be done for long periods of time. If synchronous motors are chosen to drive such pumps, an improvement of the electrical conditions of the system can be obtained at the same time.

The pumps of the Rempen power house are of this kind.

Pumps Connected with the Turbine Generator Unit. In recent years, the use of pumps coupled with the main unit is gaining much favor. From the operating point of view, such an arrangement presents a certain advantage.

If the pump is connected to the main unit by means of a coupling, then the pumping can be started only after the main generator, which has to run as a motor, is synchronized with the system.

If in emergency the main unit is called upon to deliver power, then the coupling is to be disengaged, and the generator, being already synchronized and connected to the system, can be loaded to full capacity in a short time. In this way, by means of a quick acting coupling, the main unit that is used for pumping acts as a spare unit which can be put under load very quickly.

This arrangement was first adapted to horizontal shaft units, for which it is well suited. The plan view of the pump arrangement of the Murg and Schwarzenbach power house is shown on Fig. 18. Two turbine pumps are connected by means of a gear reduction and an electric coupling to the shaft of the main unit. The electric coupling can be disengaged practically instantaneously and the generator loaded up to the whole load in a few seconds.

The experiences with the horizontal shaft arrangement were so successful that a pump for vertical shaft units was brought out on the market. As shown in Fig. 19, the pump is connected to the unit by means of a hydraulic coupling. The weight of the pump rotor and of the part of the hydraulic coupling connected to

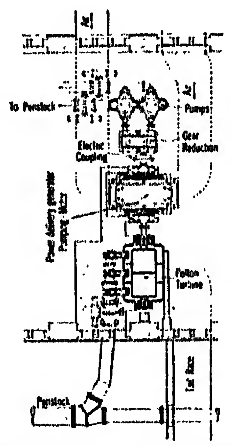

FIG. 18—PUMP CONNECTED TO A HORIZONTAL SHAFT UNIT

the pump is carried by a thrust bearing placed below the pump.

Special Lawaczeck Pumps. These pumps were proposed with the idea that at high water flows the amount of water is abundant and that if the pump has to be run only at this time the efficiency of the pumping outfit can be fairly low. Fig. 20 shows a section through a Lawaczeck pump unit installed in a submerged weir. The unit consists of directly connected pump and turbine runners. For the small heads available in such an arrangement the number of revolutions of a unit is small and the pressure developed by the pump is low. By using a battery of such units with the pumps connected in series, the necessary higher pressure can be developed only at a low efficiency.

As these pumps are to be used for only a short time every year their simplicity and low cost are of much more importance than their efficiency.

V. Power House Design

The following discussion is concerned with designs with vertical shaft turbines:

It is impossible to put down any general rules that would cover all the latest designs, but a few tendencies can be noticed.

One seldom meets the two-floor arrangement in which the power house has an easily accessible main generator

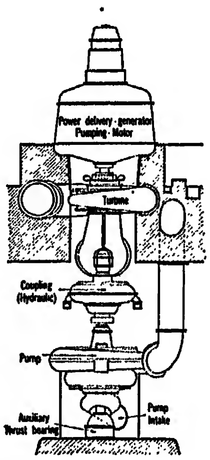

Fig. 19—Pump Connected to a Vertical Shaft Unit

floor that is covered by a crane, and a lower turbine floor not easily accessible and without the crane service. The one floor arrangement is usually preferred, in which the turbine is located in a pit of the generator floor, or else an arrangement, in which the main floor is at the turbine elevation and the generators are located on raised pedestals.

The one floor arrangement is favored for low head developments with concrete scroll cases and the arrangement with generators on raised pedestals is favored for medium head development with steel scroll cases.

The auxiliary turbine equipment in both cases is served by the main crane.

The unsupported length of the building columns can become quite long at one side of the building in such designs. By having a separate generator floor with liberal openings in it and with the turbine equipment located on the turbine floor below these openings, the advantages of the one floor arrangement can be had without the disadvantages of the unequal length of the building columns.

Structurally complicated and uncertain designs are very seldom used and the tendency is to build up the power house as a combination of simple elements.

In the larger low head developments this is accomplished by the liberal use of supporting piers built into the scroll case and draft tube, which results in a design consisting of a plain system of slabs and beams supported on these piers.

Such designs are used in the Ryborg-Schworstadt and Kembs plants.

For medium head developments, the arrangement of the power plant Aufkirchen on the Mittlere Isar in Bavaria is very satisfactory from an operating as well as from a structural point of view, and is typical of many recent designs.

This power house has only a main turbine floor and the generators are raised above the elevation of this floor on a pedestal common for all generators.

The weight of the generators and the thrust bearing loads are carried down by means of arch barrels running the whole width of the generator pedestal. The arch barrels are supported by piers that are located between the scroll cases of the separate units.

The whole design is structurally sound and the power house has practically no dark and inaccessible places. Every piece of equipment can be handled by the main crane.

The troubles which many plants have experienced in past years with runners, caused some engineers to provide for the possibility of removing the turbine runner independently from the generator. For larger turbines this is accomplished by locating the generator at a higher elevation and increasing the length of the shaft between the turbine and the generator. This longer shaft has two couplings between the turbine and generator with a short piece of shaft in between. After unbolting these couplings and removing the short piece of shaft, the turbine runner can be lifted independently from the generator rotor.

Such design increases the over-all height of the power house and some auxiliary lifting devices are necessary to handle the turbine runner and to bring it within the reach of the main crane.

VI. Energy Destroying

The question of erosion of the ground at the toe of dams, as well as of the damage that may be done to the

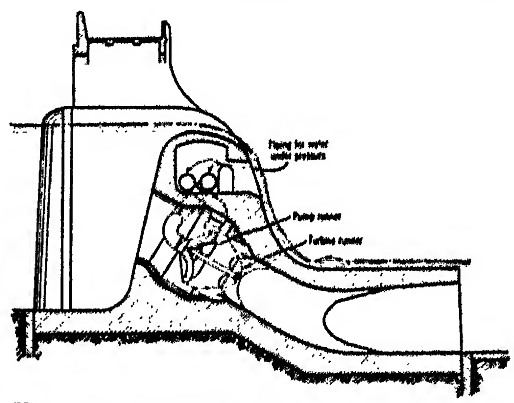

Fig. 20—Lawaczeck Turbine Pump Unit

river or canal bed by the overflow water coming down the spillway has been seriously studied in the last few years. In cases where the dam is not built on rock and the river or canal bed is not formed in rock or lined with concrete, this question is of particular importance. In order to prevent any erosion, two quite different methods have been adopted recently.

The Energy Destroyer of Baudirector Kennerknecht represents the one way of handling this problem, and the indented sill of Dr. Eng. Th. Rehbock the other.

The Energy Destroyer is built and operated in the Innwerke near Munich, Bavaria. The idea is to let the water flow down in two separate pipes at considerable velocity and to combine both water columns on the lower elevation in a reservoir that is formed in such a way that a mutual destruction of the energy of both water columns will take place and the water will flow over the reservoir at moderate velocity without any danger to the river or channel bed. The Energy Destroyer of the Innwerke has now been in operation for a number of years and works very satisfactorily. Being connected with the upper pond by means of a siphon, it regulates automatically the water level of the upper pond.

The idea put into the indented sill design is that the energy of the water leaving the spillway at a considerable velocity is effectively destroyed on a short distance of the tail race by the forming of a water roller. In order to prevent any erosion in the place where the water leaves the toe of the dam, conditions are to be created which will move the erosion of the river bed at a safe distance from the toe of the dam. The indented sill, which consists of a number of concrete teeth placed at the toe of the spillway, fulfills these requirements and the model tests at the laboratory in Karlsruhe give a most convincing picture of its action.

VII. Hydraulic Laboratories

Any attempt to get an idea about the high spots of the present day hydro power developments in Europe brings out the important part that the hydraulic laboratories are taking in these developments.

In Europe and particularly in Germany and Switzerland, there is a very efficient system of hydraulic laboratories supported by technical universities, states, and turbine manufacturers. These laboratories can be divided in the following three types:

1. River hydraulic laboratories which are working mainly in the line of investigation of behavior of rivers under different conditions, the influence of hydraulic structures such as dams, spillways, etc., on the behavior of the river, movements of river beds, and erosions of river and channel beds, river regulation problems, etc.
2. Turbine laboratories in which the work is mainly concentrated on turbine testing problems, cavitation, pitting, water flow in pipes, scroll cases, draft tubes, etc.
3. Naval laboratories that are mainly working on the problems connected with ship design.

The laboratories of the technical universities are of all three types, the state laboratories are mostly river and naval laboratories, and turbine manufacturing concerns have turbine laboratories.

Considering only the river and turbine laboratories, it is to be noted that the progress in hydro development in Europe is due to the close and most beneficial co-operation and friendly competition which exists among these different laboratories.

The laboratories connected with the technical universities and states have more time and a better opportunity to do new development and research work, to check over and correct the work of other investigators, and to make special investigations necessary for the proper design of different hydraulic structures.

The work of the laboratories connected with the turbine manufacturing concerns is necessarily rather limited by the pressing every day problems that arise in connection with the designs in which the particular concerns are interested. Only at irregular intervals when the pressure of the immediate work is released can such a laboratory attempt to do any new development work. The division of work among these different laboratories and free exchange of information are responsible for the present day high standing of the low head developments in Europe.

Here are a few of the more interesting problems in connection with the laboratory work:

Scale of Models. Two different opinions predominate in the question of the scale on which models such as rivers, channels, locks, dams, etc., should be made and tested.

One opinion that is best represented by the Hydraulic Laboratory of the Prussian State in Berlin, is that the models have to be as large as possible; the other opinion, best represented by the Hydraulic Laboratory of the Technical University of Karlsruhe, is that the models are to be reasonably small depending on the character of the problem to be studied.

The Berlin Laboratory in logical development of its idea went so far as to start to build an out-of-doors laboratory outside of Berlin, in order to remove the limitations that are put on the scale of the models by the size of a building. In this laboratory models as large in scale as 1:40 are built and tested.

In order to work on still larger scales, this laboratory goes so far as to build and test models with different horizontal and vertical scales.

The Karlsruhe Laboratory stresses the importance of the refinement of measuring and observation methods and believes that a small model can be tested out much more thoroughly by making a larger number of tests under different conditions, a procedure that would be prohibitive on account of time and cost in a large scale model.

Both laboratories have the support of outside technical opinion. The Berlin Laboratory is starting a number of model tests on river regulation problems in Soviet Russia which are to be run on out-of-door models of large scale. The Karlsruhe Laboratory is finishing a special building where the regulation problems of the Rhine River are to be solved on models of much smaller scale (1:200). The tests are to be run on a number of separate models, each representing consecutive stretches of the Rhine River about 10 km. long.

Water Measuring Devices. In testing full sized turbines, the exact measurements of large amounts of water are necessary. The existing methods are cumbersome and unsatisfactory, and research in new water measurement devices is going on.

At the Technical University in Munich a thermoelectrical device is being developed, which, if successful, promises to be quite an improvement. The idea consists in having a wire in a glass tube heated by electric current and the temperature of the wire measured by a thermocouple. If inserted in running water, the device can be gaged so as to give the water velocity as a function of the water temperature. By inserting a number of such devices, for instance in a penstock, the mean velocity of the water and the quantity of it could be determined quickly and easily by measuring the water temperature and the potential of the thermoelectrical couple.

VIII. Cavitation Laboratories

The importance of cavitation and the necessity of cavitation studies led to the development of special cavitation laboratories.

The purpose of the cavitation investigation is to determine the exact conditions of draft tube head and water velocity at which the cavitation will start in a particular turbine.

By determining the efficiency of the turbine by the usual methods at different draft tube heads and drawing the efficiency curves, an approximate idea of the conditions at which the cavitation starts can be gained by the drop of the efficiency curve.

Very sensitive measuring methods are necessary to determine the exact point at which the cavitation starts, since the efficiency curve drops at the beginning rather gradually.

Other methods seem to give better results.

The cavitation laboratory of the Escher Wyss Company in Zurich uses very successfully the stroboscopic method. The model of the runner can be observed during the test through a glass window; the observer covers his head and the glass window with a dark cloth as in an old-fashioned photographic camera and illuminates the runner by an electric lamp, which is electrically connected with the runner by means of a commutator and gives one flash for each revolution of the runner. When observed by means of this lamp, the runner appears immovable irrespective of the number of revolutions it actually makes. So long as no cavitation occurs, the water appears perfectly clear. The exact moment at which the cavitation starts can be determined because of the small bubbles of vapor and air that appear along the outer circumference of the runner as a slight fog. With increase of the speed or with the increase of the draft tube head, the bubbles increase in size and number until finally the water becomes very turbulent and opaque.

In such tests a full sized draft tube head must be available which usually forces the location of such a laboratory on a higher floor and the extension of the draft tube down to the lower floors.

Laboratories and Low Head Developments. The laboratory cooperation is particularly important in low head developments. An old fashioned Francis turbine can be designed on a drafting board and the performance of the turbine designed in such way can be very closely predicted without any model tests.

A propeller or Kaplan turbine can be properly designed only if the preliminary drafting board design is modified and improved in accordance with model tests.

The conditions under which cavitation can be avoided can be determined only if the chosen shape of the blade is tested in a cavitation laboratory.

The turns of the blades of a Kaplan turbine corresponding to the position of the wicket gates, the shape and size of the draft tube partitions and of the supporting piers in the draft tube and spiral case can be determined by model tests only.

Not only the turbines, but the design of the entire power plant is to be supported by laboratory tests. The large amounts of water to be handled and the inability to determine without tests the influence that the proposed structures will have on the behavior of the river, are making the laboratory help of utmost importance. The expenses and time loss that are involved in laboratory tests are saved in more economical structures and better designs resulting from such tests.

Design of the Ryborg-Schworstadt Power Plant. A good general idea about the way in which more important low head designs are handled and about the amount of cooperation between the power plant designer, turbine manufacturer, and hydraulic laboratory can be gained by considering the way in which the design of the Ryborg-Schworstadt development was worked out.

First, a preliminary study of the development was made and the approximate location of the proposed dam and power house were determined. This information was given over to the Karlsruhe Laboratory where a complete model of the part of the Rhine River involved in this development was built. Extensive series of tests were made in the laboratory to determine the proper location of the dam and power house, the amount of river protection necessary above and below the dam, the conditions to be met to protect the shipping interests, the possibilities of sand and gravel accumulation at the intake, the influence of the cofferdams, and so on. At the same time the three turbine manufacturing concerns that were chosen to deliver the Kaplan turbines, J. M. Voith in Germany, Escher Wyss & Co. and Atelier des Charmilles in Switzerland, made preliminary designs of the turbines, built models of them, including scroll cases and draft tubes, and tested the models to determine the efficiency, the cavitation limitations, the runner blades adjustments, the shape and location of the dividing partitions and supporting piers, etc.

The results of tests made in Karlsruhe, as well as

tests made by the turbine manufacturers, were put before all parties and the necessary modifications in the preliminary design were discussed and decided.

In this way the preliminary design was modified a number of times until the best possible combination was found and the final design that is now in construction was decided upon.

IX. Concrete Work

The progress made in the past few years in the United States in proper control, mixing, and handling of big masses of concrete, has not yet reached Europe. Observations made in Germany and France showed that the concrete work was mostly done in an old fashioned way.

In the United States, the uniformity of the concrete work and the predetermined strength and density of the concrete are assured by:

1. Proper proportioning and mixing of the aggregates.
2. Strict maintenance of the necessary water-cement ratio.
3. Transportation of the concrete and disposing of it in forms in such a way as to prevent any segregation of the aggregate.

These important considerations are very often neglected in Europe. The work is mostly conducted on an arbitrarily chosen cement-sand-broken stone ratio and no strict water-cement ratio is maintained, the amount of water being left to the discretion of the foreman. In line with this absence of scientific control, the tendency that is so pronounced in the States to reduce the number of mixing plants and to have the mixing done in large mixers and in properly equipped and controlled plants is also absent. Small mixers under the direct control of the foreman in charge of the particular part of the job are mostly used. As a result, the concrete work is poor, from the American point of view.

In a properly conducted American job, the concrete is sound and equally dense throughout the whole thickness, but the outside will look rather rough, showing usually the marks of the forms. If for some reason a top coating of concrete mortar is desired, it can be applied properly only by using some instrument to roughen up the surface of the concrete after the forms are stripped.

In most of the European jobs, the concrete is porous and of non-uniform quality and a top coat of mortar can usually be applied on the green concrete without any preparation. This top coat is one of the most important parts of a European job. The applying of the top coat is a highly specialized operation, which is controlled only by the personal knowledge and experience of the cement finisher. He not only personally determines the ratio of fine and coarse sand and cement, but in most cases the mixing is made by hand and in small quantities, under his personal supervision. After mixing, the top coat is applied by hand and troweled by steel trowels.

Such a job will have at the beginning an unusually smooth and neat appearance. But, in a comparatively short time, the top coat will crack and loosen and fall off. The appearance of concrete work only four or five years old in some cases is appalling, particularly after last year's severe winter.

Besides the poor quality of the concrete work, the very long time necessary to finish a development in Europe probably depends partly on these many irregularly operated individual mixing plants. As they cannot be properly controlled and regulated, their combined output is much smaller than it could be if all the mixing were concentrated in one or a few larger plants and the concrete handled in large quantities and more regularly.

Acknowledgment

The very hospitable, helpful, and frank way in which different developments were shown to the writer, as well as the free way in which interesting and valuable information was given, are to be noted.

The trip itself was made possible by the assistance and support which the writer received from Messrs. E. S. Fickes, J. W. Rickey, and C. H. Moritz, of the Aluminum Company of America.

It is impossible to thank all the concerns and individuals who were so kind and helpful and here only a few of them can be named:

The Escher Wyss & Co., of Zurich, Chief Engineer J. Moser and the engineers, A. Messikammer, J. Ackeret, and E. Seitz of this company, the Ateliers des Charmilles S. A. of Genèva, the Director R. Neeser, and the engineers, A. Blum and G. Bavet of this company, Prof. Dr. Eng. D. Thoma in Munich and Prof. Dr. Eng. Th. Rehbock in Karlsruhe, and many others.

Discussion

F. A. Allner: Mr. Karpov's observations on the status of hydraulic research work in Europe are of great interest to engineers who have to deal with low and medium head developments.

There has been until very recently a lack of adequate laboratory facilities in this country, especially of those required for the study of the cavitation problem. For this reason one of the major hydroelectric companies in the East found it necessary to build a cavitation laboratory of its own immediately adjacent to an existing development of about 55 ft. head, where turbine models, complete with settings as proposed for another low head project on the same river, are now being tested for cavitation behavior.

Facilities have also been provided for making tests on model structures, such as, spillway sections, sluice gates, flashboards and other similar structures.

It is possible to test a 16-in. turbine model in this laboratory under a full operating head of 50 to 55 ft. and vary the draft head on the runner from 10 ft. submergence to 10 ft. draft head. These wide limits are essential in making the tests for cavitation. Cavitation is determined by two independent methods: First, a graphical method wherein an efficiency curve is drawn for constant operating conditions, with the exception that the draft

head is varied. The draft head at which cavitation starts can be determined by a sudden dropping of efficiency. The second method, used more recently by the cavitation laboratories in Europe, is the visual method for which more positive results are claimed. In order to use this visual method, the laboratory at Holtwood has been designed with an observation chamber just below the turbine setting, with glass windows in the draft tube at about the elevation of the turbine runner. Through the use of a stroboscope, it is possible to see the water leaving the runner blade and also to see the formation of air bubbles in the draft tube in the vicinity of the runner.

The laboratory normally uses about 50 cu. ft. per sec.; the exact quantity being measured by a Venturi meter tube, which has been calibrated in place by a weir as well as by the Allen salt velocity method. The power is absorbed by a 300-hp. electric dynamometer specially designed and built for vertical operation by the General Electric Company. To maintain constant conditions for a given test, the laboratory has been provided with a large head tank of approximately 350 sq. ft. area and with a pond of even larger surface area for the tailrace. Both water elevations are maintained constant by using long spillway sections.

We are obtaining valuable information concerning cavitation through this laboratory, so that we hope to be able to predict the highest elevation at which the runners at the new project may be set without encountering pitting.

By locating the runner as high as is indicated from the results of the cavitation tests, substantial economies can be secured in the cost of structures and in the amount of excavation required in the river bottom, not only under the power house itself but also in the tailrace downstream.

A. V. Karpov: Last year when I was making the necessary arrangements for my European trip and discussing my plans with friends, most of them thought that such a trip would give a considerable amount of information, but one of them was very skeptical. His line of reasoning was that a single manufacturer in the States produces more horsepower in hydraulic turbines than a whole European country and under such conditions what could be learned in Europe that is not already known in the States.

When I called his attention to the extensive laboratory work that is going ahead in Europe, his reply was that the extensive laboratory work was necessary because of the lack of practical experience and that in the States the manufacturers are backed with such a wealth of previous experience that they can achieve better results with a moderate amount of laboratory work.

In Europe I had the opportunity to discuss with one of the outstanding men in the field of hydraulic laboratory research the difference in amount of hydraulic laboratory work done in Europe and the United States. His opinion, based not only on his knowledge of the conditions in Europe, but also on the experience of a recent American trip, is very characteristic:

"Engineers in different countries are very much alike and try to bring their work to conclusion as quickly as possible. In the States they are supported in this desire by the easy way in which money can be spent in a rich country and instead of building and testing a model on a small scale, they go ahead and build a model to a scale 1 to 1 and test it.

If the test is satisfactory, the model stays as a finished work; if the test is unsatisfactory—well—then more money is spent and the necessary changes are made until everything seems to be satisfactory.

In Europe the money does not come so readily and much more strict technical proofs are required in order to get the money.

The only way to furnish such proofs is to make model tests and they are made not to the scale 1 to 1 but to a much smaller scale.

Incidentally, the necessity to make a small model usually results in a better development because if some one works on a small scale model, he, as a general rule, is not satisfied if everything looks all right at the surface, but out of all the possible combinations he tries to find the one that is the most satisfactory and in most cases it is a vast difference between something that is taken at random and is just satisfactory and a thing that is worked out thoroughly and arrived at by exclusion of all the "just satisfactory" solutions and accepting only the best.

Of course, if you have a model to the scale of 1 to 1 no research of any magnitude can be done and very seldom improvements are made even if the necessity of them is realized."

This opinion shows in a nut shell the difference between the present hydro power practise in Europe and in the States.

Most of the countries of Europe are in the stage that we in the States, or at least in the eastern part of the States, are just approaching:

The more favorable sites are developed and the new developments have to be made at sites that in the past were considered uneconomical and can be developed only if improvements are possible that will make the developments more economical.

One point of general interest, is the more individualistic way in which large developments are often handled in the States. In Europe, if you will try to follow the history of a large development, you probably will notice a greater spirit of cooperation between different parties taking part in the development which brings the necessity of much stricter proofs for each statement in order to have them accepted by all parties concerned.

The cavitation problem gives a very vivid picture of the different points of view in Europe and in the States.

A comparatively short time ago, the American practise in water power machinery was more advanced and superior to the European practise.

In the high head developments the American designed Pelton turbine was leading. In the field of the medium and low head developments, the American designers were the first to realize the importance of high specific speed turbine runners for the economical exploitation of such developments. The conservative Francis turbine design was changed, the runner diameter was made smaller and the modified higher specific speed runner was developed in this country. The development of the runner cut down considerably the initial cost of the medium and low head developments, but brought a new difficulty that was not encountered in the older designs. This difficulty, known as the cavitation phenomenon, with the resulting pitting, was increasing with the increase of the specific speed and proved to be in many cases very disastrous.

No real scientific laboratory work has been done in the States and a general mistrust against research in still higher specific speed runners developed and was so pronounced that the work in this direction was very much hampered and the American designers did not pursue the logical evolution of the idea of high specific speed turbines. All the subsequent research along these lines was made in Europe and culminated in the successful introduction of propeller and Kaplan turbines.

The credit for a scientific investigation of this matter and for the establishing of the first turbine cavitation laboratory is due Dr. D. Thoma, who, after considerable theoretical work, built the laboratory in 1924 as an addition to his hydraulic laboratory in Munich and formulated the conditions under which the cavitation tests on models have to be run in order to be applicable to full size turbines.

The fact that European turbines built in later years are practically free from cavitation troubles and the very remarkable development of large propeller and particularly Kaplan turbines in Europe in the last 10 years, is the direct result of the scientific investigations made in a number of cavitation laboratories in Europe.

Today, when ordering a turbine in Europe, the manufacturer can supply exact information about the limiting conditions under which, for the particular kind of turbine, the cavitation will occur and the whole design can be based on this information. In the States the manufacturer has only the idea that under high

setting and high specific speed cavitation will occur, but he is unable to give exact information as to when it will occur. Under these conditions the power house design is based on an argument, the manufacturer trying to persuade the customer to use against his better judgment low settings and low specific speeds and in this way to increase very considerably the cost of the whole development. It may sound as a joke, but actually developments involving hundreds of thousands of horsepowers are settled in one or in the other way depending on how convincing the manufacturer is in his arguments. The results are the extravagant expensive developments or the cavitation troubles and they can be seen in very many places in the States.

Another interesting point in the European developments which I tried to bring out in my paper, is the handling of the concrete work. Our way of controlling the mix and the handling of the concrete is much superior, and the equipment used in Europe can hardly be compared with the equipment used in our high grade jobs. Here I believe the credit is due the Portland Cement Association, not only for its very advanced research work but also in a larger degree for its consistent educational campaign. No doubt the results of the research made in concrete work in the States are known the world over, but the practical application of this research lags considerably, due to the absence of a powerful and progressive organization to spread the theoretical knowledge in the field.

In the presentation of my paper, I aimed to stress the more important principal points, instead of giving an abstract of the paper itself. The most important point, to my belief, is that at present only the industries that realize the importance of high grade research and make an honest effort to carry such research are going ahead.

That sounds like a platitude, but the comparisons that I drew seem to justify the necessity of repeating once more this simple truth.

The main reason for the presentation of my paper was to stress our shortcomings in theoretical and laboratory research work. The absence in the States of a cavitation laboratory was considered as a very serious drawback in the progress of hydro-power developments and Mr. J. W. Rickey, Chief Hydraulic Engineer of the Aluminum Company of America, called a conference of hydraulic turbine users and manufacturers, on November 4th and 5th, 1929, in Pittsburgh, Pa., to discuss the question of creating such a laboratory in the States. The fact that just lately two such laboratories were completed, the one by a large turbine manufacturing concern and the other by a large turbine user, is very gratifying. If the work in these laboratories, and in others that probably will follow, is vigorously pushed ahead, it is to be hoped that the States will again lead in low head hydraulic machinery, with the result that a large number of new sites can be successfully developed.

Automatic Stations

ANNUAL REPORT OF THE COMMITTEE ON AUTOMATIC STATIONS*

To the Board of Directors:

In accordance with established precedence, your Committee on Automatic Stations submits a review of the past year's development and application of automatic stations.

The committee terminates its third year of activity having kept in step with, and encouraged the rapid advancement in, the development of automatic equipment. Automatic equipment is assuming a most important role in every branch of the electrical industry. Along with these activities the committee has established, so far as possible, coordination of its own functions. This has been made possible by the farsighted organization perfected during the first year of the committee's existence and has accomplished in part the compilation of technical data in the form of subcommittee reports. It has also made possible the first technical session on automatic stations, in the presenation of six technical papers at the Summer Convention of 1930.

The application of various types of automatic equipment has become so extensive that no attempt has been made to cover the multiplicity of uses, it felt that the general phases have been considered in the arrangement of the technical papers for the Summer Convention and the subcommittee reports contained herein.

The committee has suffered a great loss in the untimely death of Walter H. Millan of St. Louis, Missouri, on November 13, 1929. Mr. Millan was Chairman of the Committee on Automatic Stations for the years 1928-1929. His death removes from among us an engineer of distinction, a loyal friend, and a sincere supporter of the ideals of the American Institute of Electrical Engineers.

Developments

Numerous developments have been completed during the past year; many of these are concerned principally with telemetering systems while others have been undertaken with a view to simplicity and standardization. The automatic control of power rectifiers has reached a high degree of perfection, particularly in the field of railway electrification.

Some development has taken place in the use of carrier current for operating remotely located switching equipments and in accomplishing telemetering. There seem to be possibilities in this field.

*COMMITTEE ON AUTOMATIC STATIONS:
F. Zogbaum, Chairman,

P. H. Adams,	H. C. Don Carlos,	Otto Naef,
Caesar Antoniono,	Joseph Hellenthal,	M. E. Reagan,
L. D. Bale,	E. L. Hough,	Garland Stamper,
G. O. Brown,	Chester Lichtenberg,	L. J. Turley.
	S. J. Lisberger,	

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

Operating Experiences

Considerable operating data have been collected in the past years, not only by the Committee on Automatic Stations but by other national organizations. Although operating experience is and always will be an important factor, it now seems that with the increasing stabilization of operating performance, it will be possible to look upon this as a matter of routine.

Standards

Standards No. 26, Automatic Stations, has again been reviewed by the committee. Recommendations for revisions in the list of device function numbers and in the table of minimum protection for power apparatus have been forwarded to the Standards Committee.

It is recommended that Standards No. 26 be reviewed and revised annually by the Committee on Automatic Stations.

Standardization of Symbols

A subcommittee, (Messrs. C. Lichtenberg and M. E. Reagan), was appointed to investigate and determine to what extent standard A. I. E. E. symbols were being used on diagrams for automatic stations. This subcommittee reported that these symbols are being used very generally. It was determined, however, that the present symbols are inadequate, and it is recommended that the succeeding Committee on Automatic Stations review this subject and propose additional and revised symbols.

Technical Papers

The following six papers are being presented under the auspices of the Committee at the Annual Convention, Toronto, Canada, 1930:

1. *An Electron Tube Telemetering System,* by A. S. Fitzgerald.
2. *Development of a Two-Wire Supervisory Control System, with Remote Metering,* by R. J. Wensley and W. M. Donovan.
3. *Centralized Control of System Operation,* by J. T. Lawson.
4. *Automatic Power Supply for Steel Mill Electrification,* by Robert J. Harry.
5. *1000-kw. Automatic Mercury Arc Rectifier; of the Union Railway Company, New York,* by W. E. Gutzwiller and O. Naef.
6. *Miniature Switchboards,* by Philip Sporn.

Meetings and Papers

In connection with the presentation of technical committee annual reports, the presentation of technical papers, and the discussion thereof, the Committee recommends that:

1. The reports of technical committees be presented at the special sessions of the committee held during the Annual Convention.

2. Discussion of papers to be presented at technical sessions be scheduled just as papers are now scheduled.

3. Advance copies of papers for technical sessions be in the hands of those selected to discuss them at least seven calendar days before the papers are to be presented.

Communications from Other Committees

This committee received from the Committee on Instruments and Measurements, for comment, a set of definitions covering the various phases of telemetering. These definitions were reviewed and comments forwarded.

Unfinished Business

The following topics have been under consideration, but no final reports have been rendered:

1. Fire Protection.
2. Economical Construction.
3. Unusual Operations.
4. Load Dispatching.
5. Wire Designations.
6. Suppression of Noise.

Subcommittee Reports

Two comprehensive subcommittee reports were prepared and are contained herein as follows:

Automatic Substation Ventilation*

The purpose of substation ventilation is to maintain within economical and safe limits the temperature rise of electrical apparatus installed therein. This is best accomplished by using outdoor air as a medium on the natural or forced draft principle. During early installations with small capacity electrical machinery and with ample space allowance in buildings, natural ventilation predominated. There were a few exceptions where high temperature rises required more adequate ventilation by the use of blowers or fans. With the gradual growth and development of larger units and the concentration of greater kilowatt capacity within a given area or volume (especially in basements and the crowded metropolitan areas) the problem of effective ventilation became more serious and led to a more scientific application of the various elements.

Practically each installation requires special consideration. The problem of suitably arranged and properly sized inlets and outlets; the location of air ducts for the best directed means of reaching typical suction areas on rotating type machines; the requisite as to quantity and velocity of cool air, together with preventive means of recirculation, are factors involved in the study of realizing the most effective ventilation.

With manually-operated stations, the temperature rise of ambient air caused from recirculation, together with the entire room temperature, must be governed for comfort of operators to meet summer or winter conditions. With partially or totally enclosed rotating units, an effective means has been found in controlling recirculation by conveying the heated air direct to outdoor outlets.

Sound-proofing of buildings and attempts at noise prevention with automatically controlled substations have developed the more elaborate system of forced draft. It is a matter of spending energy to handle the necessary volume of air against the resistance of bafflers, sound absorbing material, circuitous routes of air duct lines, and air filters, or washers.

Many valuable articles have been published covering actual installations with complete data on the various methods employed to ventilate effectively both machine and substation building to which reference is hereby directed.

*Contributed by L. J. Turley.

Bibliography of Substation Ventilation Articles

1922

Campbell, G. E., "Noiseless Automatic Substation for Los Angeles Railway," *Elec. Ry. Journal*, Vol. 60, July 8, 1922, pp. 37-38.

1924

Hague, F. T., "Ventilation and Noise Control of Substation Machinery," *Elec. Jour.*, Vol. 21, March, 1924, pp. 107-11.

Turley, L. J., "Progress in Noiseless Substation Design," *Elec. Ry. Journal*, Vol. 63, April 26, 1924, pp. 645-51.

Anonymous. "Substation Ventilation," *N. E. L. A. Proc.*, Vol. 81, 1924, pp. 740-49.

"Ventilating Transformer Vaults Systematically," *Elec. Wld.*, Vol. 84, Dec. 6, 1924, p. 1213.

Report, A. E. R. E. A., "Power Generation and Conversion," Committee No. 3.

1925

Greene, A. L., "Automatic Substations Cooling Systems," *Elec. Wld.*, Vol. 85, Jan. 17, 1925, pp. 152-53.

Sieber, F., "Ventilation of Transformer Vaults." (In German.) *E. T. Z.*, Vol. 46, Jan. 22, 1925, pp. 115-17.

Turley, L. J., "Improved Ventilating Features in Los Angeles Automatic Substations," *Elec. Ry. Journal*, Vol. 66, Aug. 1, 1925, pp. 153-57.

Van Hook, L. N., "Ventilation of Automatic Substations," *Electric Traction*, Vol. 21, Sept. 1925, pp. 485-488.

Report, A. E. R. E. A., "Power Generation and Conversion," Committee No. 3.

1926

Anonymous, "Sound Proof Automatic Substation," *Electric Traction*, Vol. 22, July, 1926, p. 369.

"Cooling of Automatics is Important," *Coal Age*, Vol. 30, Aug. 12, 1926, pp. 218-19.

Report, A. E. R. E. A., "Power Generation and Conversion," Committee No. 4.

1927

Dohme, W., "Structural Features of Transformer Stations." (In German.) *Siemens-Zeits.*, Vol. 7, July, 1927, pp. 498-508.

Anonymous. Report A. E. R. E. A. Committee on Power Generation and Conversion. *Elec. Rwy. Journal*, Vol. 70, Oct. 8, 1927, pp. 700-1.

REPORT, A. E. R. E. A., "Power Generation and Conversion." Committee No. 2.

1929

BROCKNER, R. P., "Heating in Automatic Substations," *Power*, Vol. 70, Sept. 3, 1929, p. 373.

ANONYMOUS. "Condensation in Substation Eliminated by Heater," *Elec. Wld.*, Vol. 94, Nov. 2, 1929, p. 882.

1930

SOHLBERG, G., "Substation Ventilation," *G. E. Review*, Vol. 33, Feb., 1930, pp. 104-11.

GUIDE TO SPECIFICATIONS FOR AUTOMATIC SWITCHING EQUIPMENTS*

In the application of automatic switching equipments, certain fundamental factors apply equally well to all service classifications; others are necessarily specific. This guide is prepared with the desire to aid in the selection of the type of equipment with proper operating characteristics for a given service. This is given in outline form to call attention to the factors to be considered in this selection.

In general, the various devices comprising the automatic switching equipment should be chosen to meet the interrupting rating, short time rating, continuous and overload rating for the particular service.

GENERAL

I. Selection of equipment for automatic service varies slightly from that chosen for manual control.

A. Usually smaller units nearer load centers.
   1. Better voltage regulation.
   2. Saves distribution losses.
   3. Saves feeder copper.
   4. Smaller real estate and buildings.

B. Determination of loads and load centers. (In laying out plans of system, several schemes should be considered. Refer to published data. See A. E. R. A. Eng. *Proceedings* as example for railway work).
   1. Survey and analysis of load requirements.
   2. Spot load centers.
   3. Scheme and type of machine. (See "Machines" under F.)
   4. Spare units or portable substation.

C. Economic study.
   1. Determination of total investment and annual charges for the several schemes, including transmission, conversion, and distribution.
   2. Calculation and tabulation of losses.
   3. Considerations of factors such as:
      a. Ratio of unit size to total capacity.
      b. Desirability of multiple unit stations.
      c. Standardization on one size of unit.
      d. Availability of station site.
      e. Overhead or underground transmission and distribution.
      f. Electrolysis mitigation.
      g. Telephone and radio interference.
      h. Type of building.
   4. Decision based on combined study of economics and practical considerations.

D. Characteristics of system.
   1. Effect of a-c. conditions.
      a. A-c. line regulation should be within recommended limits. (See A. I. E. E. Standards.)
      b. Regulation may determine type of conversion unit employed.
   2. Agreement of efficiencies of equipment with service requirements.
   3. Effect of power factor on the power price rate.
   4. Amount and character of maintenance.

E. Transformers.
   1. Considerations in selection of power and auto-transformers.
      a. Installed cost.
      b. Weight—foundations.
      c. Space.
      d. Efficiency.
      e. Fire hazard.
      f. Type.
         (1) Single-phase.
         (2) Three-phase.
         (3) Spare.
      g. Method of cooling.
         (1) Air.
         (2) Oil.
         (3) Water.
      h. Windings.
         (1) High-voltage taps for regulation adjustments.
         (2) Low-voltage taps for starting equipment.
         (3) Tertiary windings.
         (4) Connections (Δ-Δ, Y-Y, etc.).

F. Machines.
   1. Synchronous converter.
      a. Needs stable a-c. supply.
      b. Inherently a unity power-factor machine.
      c. Usually needs no special equipment to parallel with other similar units.
      d. Inherently a fixed voltage machine except when of the booster type or equipped with other means of varying the a-c. supply voltage.
      e. May require brush operating mechanism.
   2. Steel tank mercury arc rectifier.
      a. Inherently a slightly lagging power-factor machine.
      b. Requires auxiliaries for
         (1) Vacuum system.
         (2) Temperature control.
      c. Needs no special equipment to parallel with other similar units.
      d. Inherently a fixed voltage machine except when equipped with separate means of varying the a-c. supply voltage.
   3. Synchronous motor generator.
      a. May operate at leading or lagging power factor.
      b. Usually needs auxiliary apparatus to parallel with other similar units.
      c. Inherently a variable d-c. voltage machine.
      d. Generator may be provided with separate excitation.
   4. Induction motor-generator.
      a. Inherently a lagging power-factor machine.
      b. Usually needs auxiliary apparatus to parallel with other similar units.
      c. Inherently a variable d-c. voltage machine.
      d. Generator may be provided with separate excitation.

In choosing the type of unit, consider:
   (1) Installed cost.
   (2) Weight—foundations.
   (3) Space.

*Contributed by C. Lichtenberg and M. E. Reagan.

(4) Efficiency.
(5) Ventilation and cooling means.
(6) Fitting machine characteristics to the service.
(7) Noise.
(8) Stability of a-c. supply.
(9) Service reliability.
(a) Heating.
(b) Commutation.
(c) Sensitivity to short circuits, etc.
(10) Safety features.
(11) Power-factor correction.
(12) Indoor or outdoor.
(13) Fly-wheel effect.
(14) Amortisseur windings.
(15) Amount and character of maintenance.

5. A-c. generator.
a. Vertical or horizontal.
b. Speed (rev. per min.).
c. Synchronous or induction.
d. Exciting systems.
(1) Individual exciter per unit.
(2) Common exciter for all units.
(3) Exciter bus.
(4) Type of exciter drive.
(a) Direct connected.
(b) Bolted.
(c) Geared.
(d) Motor.
(e) Auxiliary prime mover.
e. Voltage regulation.
(1) Fixed field.
(2) Voltage regulator.
(a) Individual regulator for each unit.
(b) Common regulator.
f. Brakes.
(1) Oil operated.
(2) Air operated.
(3) Water operated.

6. Synchronous condenser.
a. Self-cooled.
b. Enclosed.
c. Water cooled.
d. Hydrogen cooled.

7. Rotating machine accessories.
a. Bearing thermal relay.
b. Synchronous speed device.
c. Grounding protective relay.
d. Overspeed device.
e. Rheostats.
(1) Hand operated.
(2) Electrically operated.

G. Switching Equipment.

1. Control power. (In general the source of control power chosen should be a reliable source obtainable at minimum cost.)
a. A-c. control: Particularly applicable to less complicated installations. Generally simplest and most inexpensive, making use of control battery and associated charging equipment unnecessary. Special features may be necessary to incorporate in control in order to prevent momentary shut-down on voltage dips.
b. A-c. and d-c. operation with tripping battery: Simple and inexpensive arrangement for average installations but requiring a certain amount of battery equipment. Recommended minimum tripping battery voltage is 48.
c. D-c. operating and tripping battery: Generally ideal arrangement from control standpoint for more complicated stations but results in some additional complication and maintenance due to amount of battery equipment required.
d. D-c. with pneumatically operated main circuit devices: Special adaptation used for railway service which has advantage of using standard, pneumatically operated devices used in car equipments, but has the disadvantage of requiring a continuous supply of compressed air and compound equipment.

2. The arrangement and construction of the a-c. bus and mounting of the oil circuit breakers may be of any of the following types:
a. Indoor.
(1) Safety enclosed trucks.
(2) Indoor metal clad.
(3) Cubicles.
(4) Masonry or brick cells.
(5) Welded or riveted angle iron framework.
(6) Pipe framework.
b. Outdoor.
(1) Outdoor metal clad.
(2) Outdoor oil circuit breakers.
(3) Switchhouses.
(4) Welded or riveted angle iron framework.
(5) Pipe framework.

The choice of the above is governed by the following considerations:
a. Installed cost.
b. Station construction and arrangement.
(1) Floor space.
(2) Head room.
(3) Time available for initial installation.
(4) Self contained unit construction.
(5) Future additions.
(6) Adaptability to move to new installations.
c. Operating features.
(1) Phase isolation.
(2) Circuit isolation.
(3) Interchangeability of units.
(4) Readily removable feature.
(5) Test position of breaker.
(6) Grounding and testing arrangement for breaker.

3. A-c. incoming lines.
a. Two or more lines for reliability.
(1) Parallel lines.
(2) Preferred emergency.
(a) Synchronous sources.
(b) Non-synchronous sources.
(c) Non-preferential sources.
b. Trip on unbalance, low voltage, reverse power, etc.
c. Reclose on reestablished voltage.

4. A-c. feeders.
a. Stub-end feed.
(1) Trip on overcurrent.
(2) Reclose periodically a definite number of times with time delay.
b. Multiple stub feed.
(1) Trip on overcurrent, reverse power, etc.
(2) Reclose periodically a definite number of times with time delay.

(3) Automatic synchronism check and automatic synchronizing.

5. D-c. feeders.
 a. Stub feed and stub-multiple feed.
  (1) Trip on overcurrent, undervoltage or short circuit.
  (2) Reclose after time delay on reestablished normal conditions.
  (3) Ratings and reclosing values.

H. Methods of starting machines.
 1. Transformer taps.
 2. Starting compensator (two- or three-step).
  a. Short-time rating.
  b. Oil or air cooled.
 3. Star-delta.
  a. Extended windings.
 4. Series reactor.
  a. Short-time rating.
  b. Oil or air cooled.
  c. Per cent normal starting current.
 5. Full voltage.
  a. Per cent normal starting current.

I. Protection. (For table of minimum protection refer to A. I. E. E. Standards No. 26.)

J. Metering. (For table of minimum metering refer to table in this report.)

K. Station construction.
 1. Site available.
 2. Facilities for installing.
 3. Temporary or permanent station.
 4. Portable station.
 5. Type and number of units.
 6. Provision for future units or addition.
 7. Heating requirements.
 8. Noise-proofing.
 9. Architectural harmony.
 10. Ventilation. (See automatic Subcommittee Report on above subject.)

L. Inspection and maintenance. (Refer to Automatic Substation Maintenance which forms a part of this report.)

II. Automatic railway substations

A. Characteristics.
 1. Choice of d-c. voltage (600-1500-3000).
 2. Rising, flat, or drooping machine characteristic.
 3. Ability to withstand frequent short circuits.

E. Starting and stopping indications.
 1. Low-voltage starting and undercurrent stopping.
 2. Overcurrent starting for additional units.
 3. Time switch.
 4. Supervisory control.

III. Automatic Mining Substations.

A. Characteristics.
 1. Choice of d-c. voltage (275-550).
 2. Rising, flat, or drooping machine characteristics.
 3. Ability to withstand frequent short circuits.

B. Starting and stopping indication.
 1. Local or remote control.
 2. Overcurrent starting for additional units.
 3. Time switch.

IV. Automatic synchronous condensers.

A. Characteristics.
 1. Quantity of corrective kv-a. needed (leading and lagging).
 2. Excitation systems.
  a. Direct-connected exciter.
  b. Voltage regulator.
  c. High-speed excitation.
 Means for reducing starting kv-a.
  a. Bearing oil pressure.
  b. Starting motor.

B. Starting and stopping indications.
 1. Start on high and low voltage and stop on undercurrent.
 2. Power factor starting.
 3. Time switch.
 4. Supervisory control.

V. Hydroelectric generating stations.

A. Types of prime movers.
 1. Reaction turbines.
 2. Impulse turbines.
 3. Propellor type turbines.
  a. Hand adjusted.
  b. Automatically adjusted.
 4. Vertical or horizontal.

B. Hydraulic control.
 1. Servo-motor without speed-head.
  a. Oil operated.
  b. Water operated.
  c. Electrically operated.
 2. Governor.
  a. Speed-head drive.
   (1). Motor
   (2). Belt
   (3). Gear.
  b. Starting and stopping device. (63s).
  c. Synchronizing motor.
  d. Limit stop motor.
  e. Accelerating device.
  f. Position switches.
  g. Latch for closed gate.
  h. Automatic oil pressure system.
  i. Miscellaneous valves, by passes and drains.

C. Starting and stopping indications.
 1. Float switch.
 2. Frequency relay start and underload stop.
 3. Time switch.
 4. Supervisory control.

D. Method of synchronizing.
 1. Self-synchronizing.
  a. Ratio of unit to system size.
  b. Amortisseur windings.
 2. Automatic synchronizing.
  a. Reasonable speed control at no load.

VI. Automatic lighting substations.

A. Characteristics.
 1. Two- or three-wire (250-125).
 2. Method of voltage regulation.
  a. Pilot wire from load centers.
  b. Reenergizing dead system.
 3. Balancer sets.

B. Starting and stopping indications.
 1. Low-voltage starting and undercurrent stopping.
 2. Overcurrent starting for additional units.
 3. Time switch.
 4. Supervisory control.

VII. Automatic a-c. substations.

A. Starting and stopping indications.
 1. First unit in service continuously.
 2. Overcurrent starting and undercurrent stopping for additional units.

VIII. Street lighting circuits.

A. Types.
 1. Series.
 2. Multiple.

B. Types of control.
   1. Time clock.
   2. Resonant remote audio frequency system (500 cycles).
   3. Carrier current system.

IX. Automatic d-c. industrial substations.
A. Characteristics.
   1. Two-wire 250-volt.
   2. Method of voltage regulation.
      a. Constant bus voltage.
      b. Ability to withstand short circuits.
B. Starting and stopping indications.
   1. Local or remote control.
   2. Overcurrent starting of additional units.
   3. Time switch.

X. Automatic battery charging equipments.
A. Characteristics.
   1. Choice of voltages (to suit battery).
   2. Types.
      a. Motor-generator.
      b. Static rectifiers.
      c. Station bus.
B. Methods of charging.
   1. Trickle charge.
   2. Floating charge.
C. Starting and stopping.
   1. Continuous operation.
   2. Start and stop with main unit.

XI. Supervisory control.
A. Characteristics.
   1. Supervisory control systems employed to operate and obtain remote supervision of equipment located at a greater distance than it would be economical to carry individual wires for each device.
   2. Control wires.
      a. Construction.
         (1) Overhead.
         (2) Underground.
      b. Type of conductor.
         (1) Individual conductor.
         (2) Multi-conductor cable.
      c. Inductive interference.
      d. Ground detector.
      e. Suitable resistance and insulation.
      f. Duplicate sets of wires.
   3. Storage battery.
      a. Charging equipment.
      b. Ungrounded usually.
   4. Control equipment.
      a. Control keys arranged in form of system diagram on dispatcher's board.
      b. Interposing relays.
      c. Alarm lamps.
   5. General.
      a. Audible or visual indications.
      b. Alarm to signify any apparatus change.
      c. Indication showing equipment to which line wires are connected.
      d. Remote metering.
      e. Remote synchronizing.

Automatic Substation Maintenance

The advent of the automatic substation has brought about a change in maintenance and maintenance methods. The work has become more or less specialized, and a different type of man is required to care for this type of station. The amount of maintenance and inspection necessary to keep the equipment in proper operating condition varies with the type of equipment and its application, and with the local conditions. It is quite obvious that a hydroelectric station located away from the dirt of the city will not require nearly so much cleaning and blowing out as a railway converter station located on a busy street in the heart of the city. It is also evident that the more complicated stations will require more maintenance work than the simpler type.

This advice is based upon maintenance experience in railway converter stations and all charts and schedules cover this type of equipment. Maintenance of other types of equipment, however, parallel the railway type very closely and the only variation will be in the type of charts used and the amount of maintenance necessary.

It is assumed that the operating company has a competent crew of maintenance men well versed in general maintenace practises and thoroughly familiar with the sequence of operation of the stations which will be placed in their care. These men may be broken up into two groups—the inspectors and the regular maintenance crew. The inspectors should be men who have proved themselves especially adept in working out the causes of trouble and visualizing the conditions which could produce the troubles which they are to locate and cure. The inspector should visit the stations every two or three days, depending upon the severity of service, and make a casual inspection of the equipment. This casual inspection should consist of reading meters, taking readings on operation indicators, checking oil levels and giving the station a visual check throughout. The inspector should also be charged with the investigation of any troubles which may arise in the operation and should have complete charge of the testing and calibrating of all protective devices.

The members of the maintenance crew should be trained maintenance men and helpers working in pairs, the maintenance man doing all the inspecting and adjusting and the helper handling the air hose and taking care of the brushes and wiping down the equipment. The frequency with which this maintenance crew visits the stations will depend entirely upon the severity of the service on the station and also upon local conditions regarding dust and dirt. In general, however, it is found that a thorough blowing out and cleaning up accompanied by a general inspection about every two weeks is sufficient. It must be understood, however, that this is only a general average and that this amount of work must be increased or decreased according to the individual needs of the station.

The type of inspection reports and charts varies with the individual operating company, but in general, they all follow the same lines. There are two general forms of inspection charts in common use. One type is merely a numerical list of the devices with suitable blank spaces to be filled in by the workman. This report is very much in detail and calls for answers of the "Yes" and

"No" variety and has a slight tendency to destroy the individuality of the maintenance man; in general, it is better to let the maintenance man use his own judgment as to cotter pins, contacts, and general mechanical conditions of the various devices. Another disadvantage in this report is that with the various devices listed in numerical order, it means that to follow the report down from top to bottom, the maintenace man must keep moving from one piece of equipment to another, numerically and not according to physical location, and unless the report is followed very closely, some pieces of apparatus may be missed.

The type of inspection report or chart shown in Fig. 1 consists of a general plan of substation, with the switchboard placed flat on the floor. All pieces of equipment are shown in their relative positions by small numbered squares and the inspector or maintenace man using this chart may start at one end of the switchboard and check each panel as he goes. A common practise is to have the maintenance man use different colored pencils for checking off the equipment which he has inspected and cleaned. In this manner, if one man checks a certain panel upon which trouble is found later, he can be held accountable for not having discovered and eliminated the trouble on his previous inspection. This type of chart is also useful in that the superintendent of substations, in looking over these reports, can pick out at a glance, the devices that have caused trouble, as this is indicated by a "T" placed in the square representing the device. If the inspector or maintenance man has checked the device and found it o. k., he so indicates by a check mark in the square; but if he finds that there is trouble in this particular piece of apparatus, he places a "T" in the square, turns the inspection report over, indicating the device number, describing the nature of the trouble and what was done to remedy it. This makes a quick and convenient method of locating troubles on the chart and does not necessitate the reading of all of the details.

It is impossible to give any definite instructions regarding the amount of maintenace work necessary to keep a chain of automatic substations in the proper operating condition, as the quantity of the work is entirely dependent upon the severity of the service to which the equipment is subjected and also upon the local conditions regarding dirt, dust, dampness, etc. However, it will be found from six to eight months' experience in caring for a chain of automatic stations, just how much individual maintenance each station will require, and a schedule may be arranged accordingly.

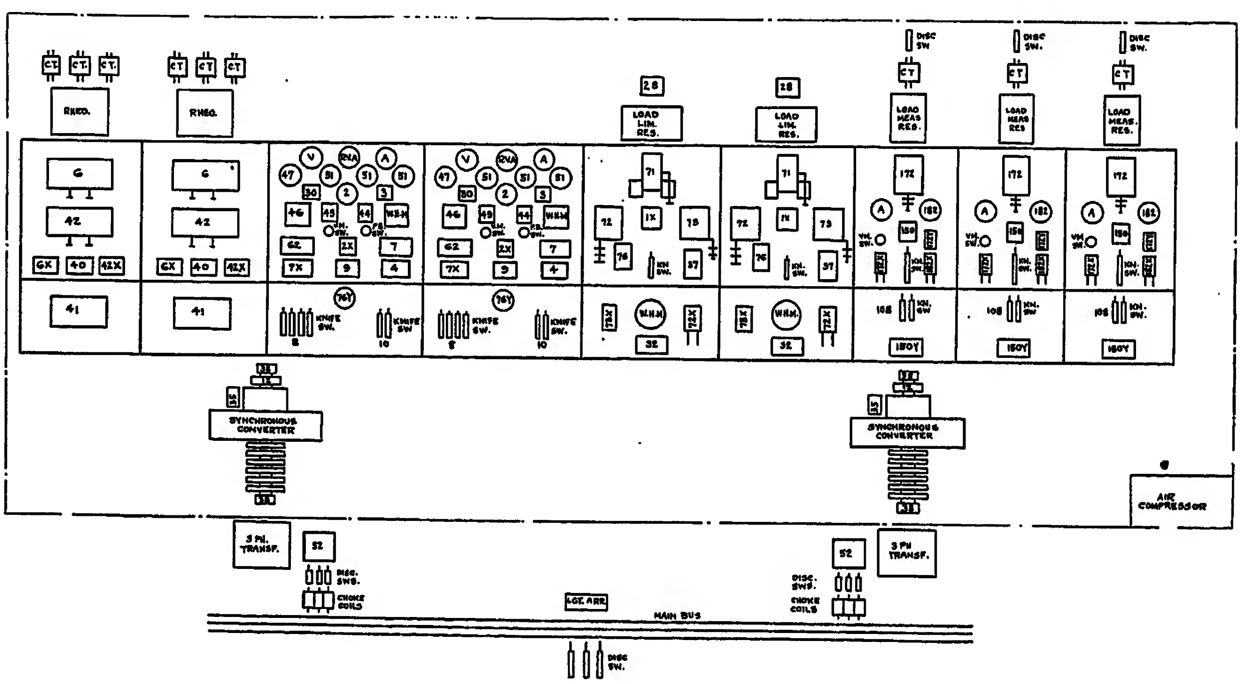

FIG. 1—SUBSTATION INSPECTION CHART

In addition to the regular maintenace work of inspecting, cleaning, and blowing out, there is a certain amount of routine testing and inspection that should be laid out and followed carefully over each year's period of operation. This type of work consists of the testing and calibrating of the various protective devices, the maintenance and inspection of bearings, and the testing of transformer oil. A sample schedule for work of this kind is given below; and while it must be understood that this schedule will not apply to all applications, it can nevertheless be used as a basis for starting an inspection and testing program:

D-c. reverse-current relays, and a-c. reverse power and machine overspeed: Test and calibrate every six months.

D-c. overload, a-c. reverse phase, and low voltage: Test and calibrate every six months.

Bearings of converters and auxiliary rotating equipment: Change oil and flush reservoirs every six months. Take out and inspect converter and motor-generator set bearings once a year, and touch up spots that show signs of slipping or cutting.

Transformer oil: Samples of oil from the oil insulated transformers should be taken every six months and tested for dielectric strength by actual test with an oil testing transformer. If the oil tests low, it should either be changed at once or else run through a dehydrating machine.

Oil in oil breakers: The amount of attention which the oil breakers in a station require is solely dependent upon the number of operations per day and the severity of the loads which they interrupt. For that reason, no *hard and fast rule* can be applied to the number of inspections required. In general, however, it may be said that the oil should be changed and the contacts inspected and adjusted every three to six months. In case the breaker does not perform very many operations it is often possible to extend this period considerably, but this can be proved only by experience.

Thermostats, grid resistance and bearing: Since they operate around 100 deg. cent., bearing thermostats are very easily tested by placing them in a deep pot of oil heated by a Bunsen burner or tinner's furnace. Grid thermostats, however, present a different problem as their operating temperature is usually around 300 deg. cent. This prohibits the use of oil, as it will boil below that temperature. However, a very inexpensive furnace for testing these thermostats may be made similar to that shown in Fig. 2.

This oven is merely a heavy sheet-iron cone, lined with asbestos and designed to fit over the top of an ordinary tinner's stove. Suspended from the closed top of this cone is another sheet-iron cone of smaller dimensions which forms a chamber for heating up the bulb of the grid thermostat, at the same time keeping it away from the direct flame of the tinner's stove. Small openings are left in the outside cone to carry away the flame and gases. The inner chamber maintains practically an even temperature, so that readings obtained from the thermometer will be equivalent to the temperature to which the grid thermostat bulb is subjected. The grid thermostats and bearing thermostats are probably the most abused of any of the protective devices in an automatic substation because, due to the difficulty of testing them, inspectors and maintenance men often allow them to remain in an improperly calibrated condition for some time without discovering that they are out of calibration. For this reason, they should be tested at least every six months in order to insure the safeguarding of machine bearings and the load-limiting resistors.

Feeder resistance measuring relays: In most applications, it is sufficient to check the calibration of these relays every six months. This work is commonly accomplished by the use of a resistance capable of carrying the measuring current and equal to the resistance of the load upon which it is desired to reclose.

The remaining protective devices can be checked during the general inspection and cleaning-up period; no special time for this work is necessary.

Insulation tests should be made on the station equipment every six months. By insulation test is meant that all control wiring, all high-voltage bus work, and all electrical apparatus should be subjected to an insulation test with a megger. In addition, on all 600-volt installations, the switchboard risers and supports should be tested for grounds and also for potential. The same applies to the cast-iron framework which supports the grid resistors. Occasionally a bank of grid resistors will be found which has broken down its insulation and

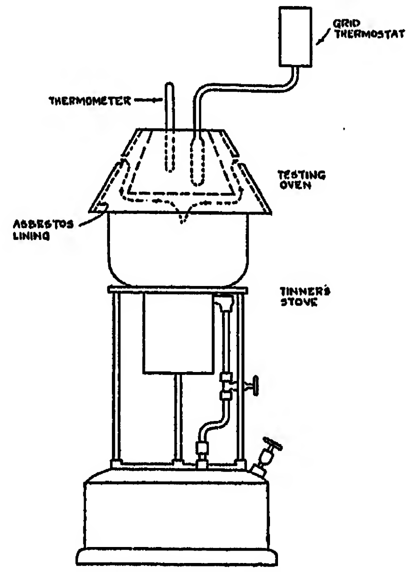

FIG. 2—FURNACE FOR TESTING THERMOSTATS

placed potential on the cast iron end frames. This is a dangerous condition, since workmen may accidentally ground these end frames and cause a bad burn-out. The subjecting of the control wiring to an insulation test often discloses some peculiar condition which would not have been discovered except through the medium of serious trouble. The use of a megger on the control wiring will often disclose minor grounds caused by collections of copper and carbon along wiring and equipment which at the time of inspection could cause no trouble but might at some future time develop into an arcing ground or short circuit which would cause serious damage. When these faults in control wiring exist an elimination process should be started by taking off connections and progressing slowly down the control wiring until the fault is located. This can be accomplished by following the schematic diagram and checking off the points as they are disconnected and cleared.

If they are to find troubles quickly and properly adjust the various relays, it is essential that the

inspectors and maintenance men be supplied with the proper instruments. A set of meters is useful for this purpose. These meters are compact and may be carried in a small leather carrying case. One is a d-c. volt-ammeter with the following ranges: 0-15, 0-150 volts with external resistor for 600 volts, and 0-3, 0-15 amperes. The other is a triple-scale a-c. voltmeter 0-150, 0-300, and 0-600 a-c. volts. Instruments of this kind can easily be carried from station to station and will always be available for testing and inspection work. Furthermore, the fact that the maintenance men have these instruments available will lead them to investigate immediately any condition which may not seem exactly right to them, while if it is necessary to secure the proper instruments from headquarters to investigate the condition, the chances are that it will be postponed and forgotten.

Automatic substations maintenance should be judged not so much by the quantity as by the quality of the work. The maintenance man who understands his station perfectly, as well as the characteristics of the individual relays, will discover while cleaning up the station troubles that the average maintenance man will pass over without notice. With this in mind, all available literature concerning the stations should be turned over to the maintenance men, and frequent classes held, in which maintenance problems and methods may be discussed. By continually bringing up new problems and new phases of the work in these classes, the men will be prevented from falling into that rut which transforms maintenance men from a state of creative and constructive thinking into one in which they turn out routine work mechanically. This condition grows out of doing the same work, day in and day out, without learning anything new about the equipment or having any reason to think deeply about its scheme or operation.

So long as the work is instructive and the men are learning through the medium of their experience in the stations, the quality of the maintenance work will be found to be of high degree, but as soon as this drops into a slow, grinding routine, a let-down in the quality of the inspection and the maintenance will be apparent.

Bibliography

In order to provide additional information for those interested, it has been the practise of this Committee to publish each year a bibliography on automatic stations. This has been done again this year and the list has been brought up to the year 1930. This bibliography is attached to this report as Appendix No. 1.

APPENDIX NO. 1

AUTOMATIC STATIONS; SUPPLEMENTAL BIBLIOGRAPHY, 1929-1930[1]

1930

AVERY, A. H., "Electrical Telerecorder," *Elec. Rev., Lond.*, Vol. 106, Jan. 24, 1930, pp. 157-59. "The electrical transmission of records of an essentially dry system, the action of which depends upon variable inductive effects in a transmitting coil situated in an alternating magnetic field."

BEARDSLEY, C. R., "Electrical Design Versus Human Fallibility," *N. E. L. A. Bul.*, Vol. 17, Jan. 1930, pp. 24-6. Outlines growth of automatic equipments.

BUESE, L. A. and GARRETT, P. B., "Better Service Through Supervisory Control," *Elec. West.*, Vol. 64, Jan. 1930, pp. 1-7.

BURTON, WM. H., "Solenoid Transfer System for Remote Indication and Record," *Power*, Vol. 71, Feb. 11, 1930, p. 221.

COLVIN, C. W., "Large Automatic Hydro Plant has High Reliability," *Elec. Wld.*, Vol. 95, Jan. 11, 1930, p. 112. Short account of operating results with the 10,000 kv-a. Alouette plant of the British Columbia Electric Railway Co.

COPE, H. W., "Supervisory Control for the New York Edison Co.," *Elec. Jour.*, Vol. 27, Jan. 1930, p. 16.

DÜHNE, W., "Power Supply of the Halle Street Railway Particularly by Means of Remote-Controlled Rectifier Installation." (In German). *Siemens-Zeit.*, Vol. 10, Jan. 1930, pp. 49-57.

HABERSAAT, L. and WEBER, B. W., "Oberforsthaus" Automatic Railway Rectifier Installation of the Municipal Power Plant at Frankfurt-on-the-Main. (In German). *A E G. Mit.*, Jan. 1930, pp. 2-10. Illustrative description of A. E. G., equipment.

LISBERGER, S. J., "Automatic Idea," *Elec. Light & Power*, Vol. 8, Feb. 1930, pp. 38-41.

LISTON, J., "Some Developments in the Electrical Industry During 1929." *G. E. Rev.*, Vol. 33, Jan. 1930, pp. 49-51.

LOHMANN, H. AND GRUNDHERR, F. V., "Flow Meter with A-c. Remote Indication." (In German). *Siemens-Zeit.*, Vol. 10, Jan. 1930, pp. 37-43.

STERN, W., "New Indicating and Recording Method for Remote Measuring." (In German). *E. T. Z.*, Vol. 51, Jan. 16, 1930, pp. 77-80.

TABLE OF MINIMUM INSTRUMENT AND METERING EQUIPMENT

	Syn. converter			Syn. motor-generator		Gen.	Cond.	Rect.	Trans.			
	Rwy. 600-volt	Edison 250-volt	Mining and industrial	Edison 250-volt	Mining and indus.	Syn. hydro.	syn.	Merc.	Static	A-C feeders	Balancer sets	Syn. motor
A-c. ammeter			X§	X	X	X	X		X*	X*		X
A-c. voltmeter						X	X					
Reactive volt-ammeter	X	X	X§									
Field ammeter				X	X	X	X					X
Main d-c. ammeter	X	X	X	X	X			X			X‡	
Main d-c. voltmeter	X	X	X	X	X			X			X†	

*Single ammeter with three-phase switch or three-phase ammeter.
†To read full d-c. voltage and voltage from either side to neutral.
‡With zero center scale in neutral.
§Either one.

1. Contributed by Main Library of the General Electric Co.

1929

A. I. E. E.—Annual report of the A. I. E. E. Committee on Automatic Stations, A. I. E. E. Jour., Vol. 48, Aug., Dec., 1929, pp. 596-8, 911-12. A. I. E. E. Trans., Vol. 48, Oct. 1929, pp. 1322-27. Includes a bibliography.

Angelis, M. L. de, "Montreal Tramways Extends Use of Mercury Arc Rectifiers," *Elec. Rwy. Jour.*, Vol. 73, Aug. 1929, pp. 778-81. Illustrated description of an automatic rectifier substation.

Anderson, A. E., *Automatic Reclosing High-Speed Circuit Breaker Feeder Equipment for D-c. Railway Service*, A. I. E. E. Trans., Vol. 48, Apr. 1929, pp. 554-62.

Bartholomew, F. J., "Small Automatic Plant in Rockies Serves Silver Mines in British Columbia," *Elec. News & Engng.*, Vol. 38, Aug. 15, 1929, pp. 39-40, 48. Automatic plant of the Cork Province Mines, Ltd.

Benziger, J. V. and Johnson, J. T., Jr., "Automatic-Frequency Control," *Elec. Wld.*, Vol. 93, June 29, 1929, pp. 1332-34.

Bertrans, M. and Sauvaire, "Devices for Remote Indication of the Presence of Sleet on Trolley Wires, and for Remote Control of Operations for Heating the Wires." (In French). *Ind. des Voies Ferrees*, Vol. 23, July 1929, pp. 267-71.

Black, S. W. and Seymour, N. F., "Small Muskoka Plant Remote Controlled," *Elec. News & Engng.*, Vol. 38, Dec. 15, 1929, pp. 48-50. Trethewey Falls automatic hydroelectric plant on the South Muskoka River, Canada.

Black, S. W. B. and Seymour, N. F., "Trethewey Falls Development," *Bul. of Hyd. Power Comm. of Ont.*, Vol. 16, Nov. 1929, pp. 377-82.

Bokkenoogen, E. V., "Supervisory Control for Industrial Substation," *Elec. Wld.*, Vol. 93, June 22, 1929, pp. 1287-8.

Borolin, P. B., "Automatic Traction Substations." (In Russian). *Elektrichestvo*, Feb. 1929, pp. 63-9. Considers the various types, their equipment, functioning, advantages and drawbacks.

Chirol, "Remote Control of Multi-Tariff Meters without Pilot Wires." (In French). 26 p., 1929. Conférence des Grand Reseaux. Electriques for 1929. Paris. *Sci. Abstr.*, Sec. B, Vol. 33, Jan. 1930, pp. 23-24.

Crellin, E. A., "Generator Fire Protection for Automatic Hydro Plant," *Elec. Wld.*, Vol. 93, May 18, 1929, pp. 975-6.

Crellin, E. A., "Irrigation Water Utilized by Automatic Hydro Plants; Spaulding No. 3 Plant of the Pacific Gas and Electric Co., *Elec. West.*, Vol. 62, April 1929, pp. 194-200, *Elec. Wld.*, Vol. 93, April 27, 1929, pp. 821-3.

Dardenne, J., "Hourat Automatic Railway Substation of the Compagnie des Chemins de Fer du Midi." (In French). *Revue Gen. de L'Elec.*, Vol. 25, Apr. 20, 1929, pp. 607-20. *Genie Civil*, Vol. 94, May 11, 1929, p. 461. Abstract. Illustrated description of methods and equipment used in the first automatically-controlled railway substation in France.

Denny, R. C., "Self Controlled High Head Hydro Plant," *Elec. Light & Power*, Vol. 7, Mar. 1929, pp. 32-34, 36, 102.

Dinapoli, D. P., "Automatic Gate Control Maintains Normal River Flow," *Elec. Wld.*, Vol. 94, Dec. 21, 1929, p. 1220.

Ding, A. P., "Application of the Automatic Substation to Steel Mill Service," *Iron & St. Engr.*, Vol. 6, Feb. 1929, pp. 78-81.

Edwon, W. W., *Automatic Transformer Substations of the Edison Electric Illuminating Company of Boston*, A.I.E.E. Trans., Vol. 48, Oct. 1929, pp. 1108-13.

Fleck, B., "Two Remotely Controlled Automatic Hydro Power Plants in South Africa," *AEG Progress*, Vol. 5, Feb. 1929, pp. 29-35; *AEG. Mit.*, No. 7, July 1929, pp. 462-67.

Garrett, A. M., *Automatic Mercury Rectifier Substation in Chicago*, A. I. E. E. Trans., Vol. 47, July 1929, pp. 925-27.

Gerell, G. W., "Direct-Tie Automatic Substation," *Elec. Wld.*, Vol. 94, July 27, 1929, pp. 186-7.

Gulliksen, F. H., *New Automatic Synchronizer*, A. I. E. E. Trans., Vol. 48, Oct. 1929, pp. 1178-88.

Harvey, R. M., "Unattended Rectifier Substation," *Elec. Engr. of Aust. & N. Z.*, Vol. 6, June 15, 1929, pp. 93-8. Describes an installation at Hurstbridge, Australia.

Hellfarth, R., "Remote-Controlled Glass-Bulb Rectifier Station of the Bremen Electricity Co." (In German). *AEG. Mit.*, No. 7, July 1929, pp. 456-61.

Hussey, F. R., "Unit Type Switch and Control Gear for Alternating-Current Substations," *Elec. Wld.*, Vol. 94, Aug. 10, 1929, pp. 270-1.

Imhof, A., "Remote Electric Measurements, Especially by Means of the Induction System of Trüb, Täuber & Co." (In German). *Elek. u Masch.*, Vol. 47, Mar. 10, 1929, pp. 189-92.

Imhof, A., "Remote Electric Transmission of Instrument Readings and the Taeuber-Gretler Induction System." (In French). *Rev. Gen. de L'Elec.*, Vol. 26, Aug. 10, 1929, pp. 217-22.

Jones, G. F., "Automatic Substations Need Systematic Maintenance for Dependable Operation," *Ind. Engng.*, Vol. 87, Aug. 1929, pp. 394-97, 424.

Keinath, G., "Development of Electrical Telemetering." (In German). *E. T. Z.*, Vol. 50, pp. 1509-14. Discussion, Oct. 17, 1929, pp. 1536-7.

Kiessling, C., "Automatic Power Plant at Surahammar." (In Swedish). *Asea Tidning*, Vol. 21, Feb. 1929, pp. 18-34.

Kiessling, C., "Automatic Power Station, Surahammar, Sweden," *Asea Jour.*, Vol. 6, July-Aug. 1929, pp. 106-23.

Kiessling, C., "Semi-Automatic Water Power Plants." (In Swedish). *Asea Tidning*, Vol. 21, July-Aug. 1929, pp. 111-17.

Kotschubey, N., "Rockfield Rectifier Substation of the Montreal Tramways, Canada," *Brown Boveri Rev.*, Vol. 16, Dec. 1929, pp. 337-40. Short account of B. B. C. mercury-arc rectifier equipment in an automatic substation.

Latzko, H. and Plechl, O., *Automatic Remote Control of the Hydraulic Equipment of the Achensee Plant of the Tiroler Wasserkraftwerke, A. G.* (In German). A.I.E.E. Trans., Vol. 48, July 1929, pp. 75-82.

Linder, C. H. and others, *Telemetering*, A. I. E. E. Jour., Vol. 48, Mar. 1929, pp. 183-85; A. I. E. E. Quarterly Trans., Vol. 48, July 1929, pp. 766-84.

Liston, J., "Some Developments in the Electrical Industry During 1928," *G. E. Rev.*, Vol. 32, Jan. 1929, pp. 51-2.

McCrea, A., "Automatic Control of Frequency and Load," *G. E. Rev.*, Vol. 32, June, 1929, pp. 309-13.

McCullough, R. Y., "Automatic Substations for Unique A-c. Signaling on Reading," *Rwy. Sig.*, Vol. 22, May 1929, pp. 165-7. Describes substations of the Reading R. R., at Nicetown Junction and Gladwyn, Pa.

McDonald, H., "Automatic Substations," *Junior Inst. Engrs. Jour.*, July 1929, pp. 437-57.

Morel, A., "Automatic Substations at Sevres and at Vitry." (In French). *Revue d'Elec. & de Mec.*, Jan.-Feb. 1929, pp. 7-23. Equipment in two French substations.

N. E. L. A.—"D-c. Substation Design Practise," *N. E. L. A. Proc.*, Vol. 86, 1929, pp. 541-626. Includes chapters on automobile Edison and automatic railway substations.

Newbury, D. F., "Electric Power Plant Equipment and Practise in America," *Elec. Jour.*, Vol. 26, Nov. 1929, pp. 515-19.

Noertker, J. A., *Street Railway Power Economics on the Cincinnati System*, A. I. E. E. Trans., Vol. 48, July 1929, pp. 912-23.

Oetiker, O., "Automatic Rectifier Installation of the Elektrizitatswerke Basel at Dreispitz." (In German). *Schweiz. Elek. ver. Bul.*, Vol. 20, Nov. 5, 1929, pp. 134-42. Illus-

trated description of equipment in an automatic substation in Switzerland.

PUPPIKOFER, H., "Starting and Paralleling the Alternators of Automatic Stations." (In French). *Schweiz. Elek. Ver. Bul.*, Vol. 20, Nov. 12, 1929, pp. 361-75.

RANDELL, R. R., "Automatic Substation Offers Low Cost Reliability," *Elec. Wld.*, Vol. 94, July 13, 1929, pp. 57-58.

ROBERSTON, T. F., "Automatic Frequency Control; New Equipment at Long Beach," *Elec. Wld.*, Vol. 94, Aug. 10, 1929, pp. 267-70.

ROBINSON, E. W. AND SPURGEON, S. J., *Automatic Reclosing of High-Voltage Circuits*, A. I. E. E. TRANS., Vol. 48, July 1929, pp. 981-87.

ROSE, H. A., "C., H. & D. Railway Modernizes Power Supply; Automatic Substations and Purchased Power," *Elec. Rwy. Jour.*, Vol. 73, Mar. 2, 1929, pp. 357-60.

SANDNER, F. AND FLECK, B., "Automatic Convertor Station Ueno of the Tokio Underground Railways," *AEG Progress*, Vol. 5, Jan. 1929, pp. 1-8. Illustrated description of the A. E. G. equipment used.

SCHÄFER, W., "AEG Remote Measuring System," *AEG Progress*, Vol. 5, Sept. 1929, pp. 295-96.

SCHLEICHER, I. M., "Distant Transmission of Measurements," *Elec. Engr. of Aust. and New Zeal.*, Vol. 6, June 15, 1929, pp. 99-102. Serial.

SCHLEICHER, M., "Load Distribution and Remote Control of Power Plants and Substations." (In German.) *E. T. Z.*, Vol. 50, Feb. 21, March 14, 1929, pp. 257-60, 379-82. Discussion, Vol. 50, Mar. 14, 1929, pp. 397-8.

SCHLEICHER, M., "Long-Distance Transmission of Instrument Readings over Lines of Any Kind and Any Length." (In German.) *Siemens-Zeits.*, Vol. 9, Mar., 1929, pp. 157-63.

SOMERVILLE, T. B., "Automatic Regulation of the L. M. S. Railway Company's Power Station at Heysham," *Met. Vick. Gaz.*, Vol. 11, Mar., 1929, pp. 225-27.

STERN, W., ""Recent Developments in Telemetering." (In German.) *E. T. Z.*, Vol. 50, Mar. 7, 1929, pp. 351-3.

STEWART, C. E., "Synchronous Selector Supervisory Equipment and Telemetering," *A. S. M. E. Trans.* (*Fuel Steam Power*), Vol. 51, paper No. 9, Jan.-Apr., 1929, pp. 29-30.

TERVEN, L. A., "Remote Metering Over Telephone Lines," *Elec. Wld.*, Vol. 94, Nov. 23, 1929, pp. 1025-7.

USENER, H., "Remote Registration in Hydraulic Plants," *Engng. Progress*, Vol. 10, May, 1929, pp. 130-34.

VETSCH, U., "Automatic Hydroelectric Stations." (In German.) *Schweiz. Bauz.*, Vol. 93, Feb. 9, 1929, pp. 63-67.

VETSCH, U., "New Automatic and Remote-Controlled Power Station at Altendorf of the Buch Municipal Water and Electricity Supply (Switzerland)," *Brown Boveri Rev.*, Vol. 16, May, 1929, pp. 159-64.

WALKER, F., "Recent Developments in Heavy Electrical Engineering," *Elec. Rev.* (*Lond.*), Vol. 105, Oct. 18, 1929, pp. 643-4.

WALTY, W., "Automatic Power Plants." (In German.) *Schweiz., Elek. Ver. Bul.*, No. 10, 1929, pp. 290-306.

WALTY, W., "Supervisory Remote Control of Electrical Generating and Distributing Stations," 1929, 18 p. Conference des Grands Reseaux Electriques for 1929. Paris.

WARD, O. M., "Maintenance Problems with Mercury-Arc Rectifiers," *Elec. Rwy. Jour.*, Vol. 73, Mar. 23, 1929, pp. 471-3. Pertains to experiences of the Milwaukee Electric Railway & Light Co. with automatic substations.

WELLS, T. J., "Supervisory Control and Telemetering Equipment," *Power Pl. Engng.*, Vol. 33, July 15, 1929, pp. 801-2.

WENSLEY, R. J., "Selective Remote Metering Equipment," *Elec. Jour.*, Vol. 26, July, 1929, pp. 329-34. Bibliography of ten entries, p. 334.

WILDE, K., "New Method for Remote Signalling by means of Power and Communication Lines." (In Swedish.) *Tekn. Tidskr.* (*Elekt.*), Feb., 1929, pp. 21-25.

WOODCOCK, W. I. AND ROBINSON, E. W., "*Carrier-Current and Supervisory Control on Alabama Power Company System*, A. I. E. E. JOUR., Vol. 48, Mar., 1929, pp. 215-18.

ANONYMOUS. ""Automatic Substations of the Keihan Electric Railway, Japan," *English Elec. Jour.*, Vol. 4, May, 1929, pp. 174-80. An illustrated description of the English Electric Co. equipment used.

"Automatic Substations; Pacific Coast Electrical Association Committee Report," *Elec. West*, Vol. 62, May 15, 1929, p. 342-59. A number of subcommittee reports of the Pacific Coast Elec. Assoc. Considers equipment, supervisory control, operating experience, etc.

"Automatic Traction Sub-Stations," *Met.-Vick. Gaz.*, Vol. 11, Apr., 1929, pp. 239-41. Metropolitan-Vickers equipment.

"Dryden Paper Company's New 2,200 Kv-a. Automatic Plant at Eagle River, Ont." *Elec. News & Engng.*, Vol. 38, Aug. 1, 1929, pp. 27-28.

"Mercury-Arc Automatic Substations in Netherlands," (In French.) *Genie Civil*, Vol. 94, Apr. 27, 1929, p. 413.

"New Telemetering Equipment," *G. E. Rev.*, Vol. 32, Sept., 1929, p. 465.

"Power Supervising Grows with Chicago Rapid Transit," *Elec. Rwy. Jour.*, Vol. 73, Feb. 2, 1929, pp. 207-8.

"Remote Control and Supervision of Electrical Power Systems," *AEG Progress*, Vol. 5, Sept., 1929, pp. 292-94.

"Rupert Automatic Substation, Portland Electric Power Company," *Elec. West*, Vol. 62, May, 1929, p. 275.

"3,000-Volt Automatic Substation Equipment for the South African Railways," *Engng.*, Vol. 127, Feb. 15, Mar. 1, 1929, pp. 212-14, 282-4.

"Westinghouse Improved, Simplified Synchronous Visual Supervisory Control," *Blast Fur. & Steel Plant*, Vol. 17, June, 1929, pp. 893-4.

Electrical Communication

ANNUAL REPORT OF THE COMMITTEE ON COMMUNICATION*

To the Board of Directors:

This Committee supervised the preparation of quite a number of papers during the year, among them being fifteen papers on technical subjects which were finally presented to the membership during the Winter and Summer Conventions. Over two hundred communication papers on various subjects were presented before the A. I. E. E. in the different sections of the country during this period.

The various branches of electrical communication engineering have made considerable progress during the year as is indicated by a summary of the principal developments referred to in the following report:

TELEPHONE SERVICE IMPROVEMENTS

During the year 1929, considerable progress was made in improving telephone service and extending its scope. The growth in the number of telephones in the United States was approximately 900,000, the largest number for any one year, representing an increase of about 4.6 per cent. The total number of telephones by the end of 1929 was approximately 20,230,000. The number of daily toll conversations increased 9.5 per cent to a total of about 3,520,000.

The acceleration in the use of telephone service by the public has been accompanied by increased programs of construction of telephone plant and equipment involving an increase in expenditure of approximately $445,000,000 or 11.8 per cent in investment during the year.

As a result of the efforts of operating and staff organization there has been improvement in local exchange telephone service. The telephone companies have opened schools for the instruction of private branch exchange switchboard operators who are the employees of subscribers. Since about one-fifth of all telephones receive service through private branch exchanges, this plan seems well justified. In addition, the operating companies are supplying an increasing number of experienced operators for private branch exchanges.

Mechanical and electrical troubles have been reduced a measurable extent and the handling of information calls has been improved by means of better equipment and improved methods.

The introduction of improved operating practises and facilities, permitting the use of simplified methods of operation similar to those employed for local business, has substantially speeded up the handling of toll service. More recently, as a further step in realizing improvements in the quality of the toll service as a whole, and particularly between widely separated points, there has been developed a general basic routing plan designed to offer the highest practicable standards of service as regards the speed, accuracy and transmission efficiency in the handling of toll messages. This plan, known as the General Toll Switching Plan, provides essentially for the basic layout and design of the toll plant in a manner which will limit the number of switches required in routing toll calls and provide generally improved transmission standards for toll connections.

TELEPHONE PLANT

The extension of toll cable continued even more rapidly during 1929 than for the previous year. Approximately 3700 miles of loaded inter-city cable were added to the system together with about 1300 miles of short-haul toll cable, making a total of 5000 miles for the year and a total of toll cable both long- and short-haul for the United States of about 20,000 miles. The greater part of this mileage is in the north-eastern section of the country, but extensions are being made rapidly in the south and west. Continuous cable plant now extends from Bath, Maine, to Charlotte, North Carolina, and westward over several routes as far as Iowa City, Iowa. An extensive mileage in operation on the Pacific Coast has been made continuous from San Francisco to Fresno. About 74 per cent of the toll wire mileage is now in cable as compared with 53 per cent five years ago. These cables, which carry about 300 telephone circuits and as many telegraph circuits, for the so-called full-sized cable, are loaded at intervals of about a mile, while repeater stations are placed about 50 miles apart.

Some of these long distance cables have been placed underground while others are suspended aerially. There are many situations where the aerial type of construction satisfactorily meets requirements and it is not so expensive as the use of conduit with manholes at regular intervals. Recently there have been introduced in this country two methods for securing more economically the advantages of the underground cable where the rate of growth does not require the frequent placing of additional cables. In one of these methods a cable, protected by means of impregnated paper, jute, and steel tape covering, is buried in the ground without

*COMMITTEE ON COMMUNICATION:

G. A. Kositzky, Chairman,
H. S. Osborne, Vice Chairman,

G. R. Benjamin,	R. D. Evans,	J. W. Milnor,
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F. J. Chesterman,	S. P. Grace,	F. A. Raymond,
R. N. Conwell,	H. L. Huber,	H. A. Shepard,
B. R. Cummings,	Ray H. Manson,	H. M. Turner,
H. W. Drake,		F. A. Wolff.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

conduit. In the second method a single fiber conduit is laid and the lead covered cable is drawn into it. In both these new methods manholes are placed only at points where loading coils are to be inserted. This results in the reduction of the number of manholes as compared to previous practise from about eight per loading section to only one.

In the application of these new methods special trench digging and filling machines are employed and under certain conditions a tractor plow has been effective in opening a trench.

Pressure testing of cable with gas to indicate leaks in the sheath is now coming into general use in connection with the installation and maintenance of toll cables.

A special high-speed cable delivery truck for use on private right-of-way has been developed to replace caterpillar type tractors and trailers formerly used for this purpose. Interesting features of this truck are four-wheel drive and two sets of tires for each wheel. One set of tires for the front wheels is smaller than the other and does not come in contact with a hard road surface, thus insuring easy steering in driving on highways. Under the most difficult conditions the speed of the truck is approximately 10 miles per hour compared with about 2 miles per hour for the tractor and trailer. On the road the truck has a speed of about 30 miles per hour.

Telephone Equipment and Circuits

The use of currents of frequencies below the voice range, for calling or ringing, permits economical types of apparatus at the terminals of the circuits but requires means for relaying the signals at each intermediate repeater station. Voice-frequency signaling eliminates this relaying apparatus, and its use on toll circuits has been extended recently by the development of improved equipment for the purpose. This new equipment employs signaling current so small that the interference into neighboring circuits is negligible and provides a degree of selectivity such as practically to eliminate false operation. The new equipment is being applied on the majority of toll circuits having one or more intermediate repeaters with consequent economy in equipment and reduction in maintenance.

The increased demand for toll service has required a corresponding increase in the size of circuit groups between cities and the extension of toll circuits over greater distances, many of these new circuits being in cable. With this increase in the number of toll circuits, improvements in testing arrangements followed, and a new type of test and control board has been developed. This provides for concentrating the toll circuit apparatus before plant attendants, in the same way as at the switchboard, together with more efficient and precise testing facilities for locating faults. Other features of the new arrangements provide for circuit flexibility to care for changes in traffic loads and plant failures and in automatic indication of circuit status for the traffic and plant supervisors.

Dial System Service and Equipment

The growth of dial system service in the United States during 1929 was rapid and is represented by an increase of dial telephones of approximately 850,000 or 24.3 per cent. Approximately 21½ per cent of the total telephones in the United States are now operated on the dial basis.

An interesting development in connection with tandem equipment of the panel type for such cities as New York, Chicago, and Boston is a new call announcer which speaks the number to the manual operators, using the same general principles of sound recording and reproduction by film as are employed for talking motion pictures. A narrow beam of light is passed through a film record of the voice to a photoelectric cell. The machine consists of 14 individual speech channels corresponding to the 10 digits and 4-party letters. These give a constant repetition of each numeral or letter with a silent interval. Connection is made automatically and in succession to the proper speech channels to make up the number wanted, the switching from one channel to the next taking place in the silent interval. The machine is common to an office and will facilitate extension of the tandem method to the more distant manual suburban offices.

Telephone Circuits in Radio Broadcasting

The use of telephone circuits for connecting long chains of radio broadcasting stations continued to increase during the past year. On March 4, 1929, during the inauguration of President Hoover, more than 30,000 miles of telephone program circuits carried the ceremonies to 118 broadcasting stations in all parts of the country, making the occasion the largest chain broadcast that has ever occurred. The exercises were also heard by many listeners in different countries through short-wave transmission.

Carrier Telephone Systems

The rapid extension of carrier telephone facilities throughout the United States continued during 1929. The increase in number of channel miles in service was approximately 135,000, or 57 per cent.

Transoceanic Telephony

The development of international telephony during the past two or three years has proceeded with such astounding rapidity that about 87 per cent of the world's telephones are now interconnected by the aid of transoceanic radio telephony.

During the year a further rapid development occurred in the use made of and in the facilities provided for transatlantic telephone service. The previously existing facilities of one long-wave circuit and one short-wave circuit have been supplemented by two additional short-wave circuits, making a group of four circuits

functioning to interconnect the continental wire telephone networks of North America and Europe.

At the Winter Convention there was presented a group of four papers under the general subject of Transoceanic Telephone Service which discussed, in some detail, these new short-wave facilities and their relation to the older facilities.

Two important extensions of international commercial telephone service during the year were the opening of service between Madrid and Buenos Aires on October 12, 1929, and between New York and Buenos Aires on April 3, 1930. These additional short-wave radio telephone systems have made possible the connection of the telephone networks of Europe and of North America with those of Argentina, Uruguay, and Chile and should be an important factor in influencing commercial and political relations between the continents.

Ship-to-Shore Telephone Service

Experiments of ship-to-shore radio telephony, which have been made from time to time since 1920, resulted in commercial service from the United States to the *S. S. Leviathan* on December 8, 1929, and from Great Britain to the *S. S. Majestic* in the middle of February, 1930. Experiments have also been made with other ships and it is expected that commercial service will be extended as fast as the necessary ship installations can be made.

This ship-to-shore service is being given in the short-wave range and requires the provision of a number of wavelengths for covering the different distances and different conditions due to time of day.

The coastal transmitting and receiving stations in the United States are located on the New Jersey coast, about 60 miles south of New York, the transmitter at Ocean Gate and the receiver at Forked River. Pending the completion of the transmitting station, a station located at Deal Beach, New Jersey, is being employed. These stations are connected with New York by wire line and the technical control of the circuit, as well as the traffic operation, takes place in the long-distance telephone building in New York.

Telephone Communication with Airplanes

The Bell Telephone Laboratories has for some time been conducting experimental and development work on the difficult problem of two-way telephone communication between airplanes and the ground. In this work two airplanes are employed which are equipped with apparatus designed to make accurate measurements and tests while the plane is in the air. Tests have shown that satisfactory two-way telephony is possible between airplanes and practically any telephone connected with the United States. In several of the tests commercially satisfactory communication was maintained between an airplane here and telephone stations in Europe. This involved radio transmission from the airplane to the Bell Telephone wire system in the United States, the transatlantic radio and the regular telephone wire system in Europe.

Largely as a result of this work two-way radio telephony for plane-to-ground communication has advanced to the point where commercial apparatus is now becoming available and regular transport planes of several lines will soon be equipped with it. This should add greatly to the safety and reliability of air transportation. In addition to the pilot receiving weather and landing conditions reports and other data, he can in return keep the dispatcher informed of his position and of the weather conditions along the airway.

International Technical Conference on Radio

The fact that in radio the nations of the world share a common transmitting medium makes it important that there be international understanding on the technical standards which are to be met in order to minimize interference. There occurred at the Hague last September the first meeting of a newly organized international technical committee, known as the International Technical Consulting Committee on Radio Communication, or, more briefly, the CCIR. The meeting was attended by some two hundred government and company technical experts from the principal nations of the world.

The findings of the committee are purely advisory, but will undoubtedly have weight throughout the world, since they represent the best world opinion obtainable upon the subject. Without going into the details, it is interesting to note that constructive proposals were adopted upon the following subjects: (1) methods for comparing the frequency standards of the different nations; (2) accuracy with which stations should be expected to hold to their frequencies; (3) the frequency intervals at which stations should be assigned.

Radio Telegraph

Commercial marine radio service was established at New York City and Sayville, L. I., with ships at sea on May 15, employing modern short-wave service as well as the usual intermediate and long-wave lengths. An additional marine station has just been completed near West Palm Beach, Florida, and was opened to general public service on February 28.

Commercial transcontinental radio telegraph service connecting the Atlantic and the Pacific Coasts was inaugurated on November 15. This service not only joins the ship-to-shore services centering at San Francisco and New York City, but also extends the Pacific Coast point-to-point and Honolulu radio circuits to New York, connecting with radio telegraph services already established, to South America and those contemplated.

An additional commercial transoceanic radio telegraph service was established between New York and Lima, Peru, on December 11. This service is conducted jointly by the Mackay Radio and Telegraph Company, operating at Sayville, L. I., and the All American Cables, Inc., operating at Lima, Peru.

Carrier Telegraph Systems

The past year has witnessed a rapid growth in the application of carrier telegraph in this country. Approximately 200,000 channel miles of carrier telegraph have been placed in service, representing an increase of about 44 per cent for the year.

Progress has been made during the year in increasing the number of carrier telegraph channels which it is possible to obtain from both open-wire and cable circuits. Furthermore, carrier telegraph and carrier telephone systems have been combined in a way to provide considerable flexibility in obtaining different ratios in the number of telephone and telegraph channels which it is possible to obtain from a given group of line circuits.

For open-wire lines suitable for the transmission of carrier frequencies, trials are under way which indicate that the number of carrier telegraph channels which it is possible to obtain from one pair of wires may be increased from 10 to a maximum of 36. One pair of wires may also provide a combination of one carrier telephone channel and 24 carrier telegraph channels, or two carrier telephone channels and 12 carrier telegraph channels.

There was a continued increase in the application of carrier current telephony and telegraphy for the efficient use of existing plants in America and Europe, especially in Spain, France, and Italy, Australia and other localities. In Australia and New Zealand notable advances have been made in carrier current communication where the great distances are peculiarly adapted to this type of operation.

Cable Telegraphy

The Western Union Telegraph Company successfully completed duplexing experiments at Bay Roberts, Newfoundland, on the Bay Roberts-Horta, and on the Azores duplex loaded cable, the development and laying of which were noted in the 1929 report. A duplex balance was obtained satisfactory for operation at 1400 letters per minute. This is somewhat higher than the speed for which the cable was designed and is several times as high as the duplex speed of any previous long cable. An ultimate speed greater than 1400 letters in each direction is possible. The artificial line for balancing the cable, as well as the cable itself, is of unusual design, in that in addition to matching the inductive loading of the cable, it was also necessary to take into account various factors which are neglected in balancing for low speed operation.

A severe earthquake was registered on most of the seismographs of the world on the afternoon of Monday, November 18, 1929, which was the cause of ten submarine telegraph cables off the east coast of North America being severed. Nearly all were broken at more than one point. The location of the epicenter, as determined from earthquake records, was given by the Dominion Observatory, Ottawa, as 44° 30′ North Latitude 57° 15′ West Longitude, and the time 3.32 : 8 p. m. Eastern Standard Time. Some of the breaks did not occur at the time of the earthquake, but several hours later which would seem to indicate that there were further tremors. No less than eight cable repair ships were immediately dispatched to make the necessary repairs. Fortunately the cable companies have duplicate cables and alternate routes so international communications were not affected to any great extent.

Airways Communications

The San Francisco-Los Angeles weather reporting network established last year on an experimental basis through cooperation of the Weather Bureau, the Daniel Guggenheim Fund for the Promotion of Aeronautics, and the Pacific Telephone and Telegraph Company, has since been taken over by the Airway Division of the Department of Commerce. Through the cooperation of the Department of Commerce and the telephone companies, similar systems have been established along the New York-Chicago airway. An even more extensive system has been put in operation for the Transcontinental Air-Transport along its air-rail route across the continent. In these systems, telephone typewriter circuits connect the meteorological collection and distribution centers. This information is relayed to planes in the air by means of radio telephone apparatus.

Printing Telegraphy

During the past year, over one hundred of the concentration equipments for printing telegraph circuits mentioned in the last year's report have been scheduled for installation and at least ten are already in operation. The operating economies expected from the use of the concentrators have been more than realized.

The increase in the number of telephone typewriters used in the Bell System was very marked during the past year. Approximately 7000 machines were added, representing a growth of about 140 per cent during the year. The number of circuit miles used in telephone typewriter service has increased by approximately 280,000 or 64 per cent during the year. The difference in the rate of growth between telephone typewriters and circuit miles is due to the rapid growth of the telephone typewriter service in local areas, where the connecting circuits average only about five miles each.

Recently, experimental telephone typewriter exchange service was installed in telephone company offices in New York, Boston, Chicago, and some adjacent cities, and the practicability of this type of commercial service was demonstrated. Telephone typewriter instruments are in a large measure as adaptable as telephone instruments and can be interconnected through special switchboards in much the same manner. A subscriber, wishing to be connected to another one in the same city or in a distant city, communicates with a switchboard operator using his telephone typewriter, and the operator makes the connection to and signals the called subscriber. After the called subscriber answers, messages are passed between the subscriber

in much the same manner as over a telephone system, except that a written record is obtained at both stations. Arrangements can also be made so that one station can be connected to a number of others and broadcast information to them.

In the private branch exchange field, a number of different types of installations of telephone typewriter switching systems were made. Several automobile manufacturing companies, for example, have found these systems very efficient for production control in their factories and warehouses. Another example is the installation used by the credit bureau of one of our large cities.

Automatic Stock Quotation Boards

The past year has seen the introduction on a fairly wide commercial basis of automatic stock quotation boards in brokers' offices for electrically recording market prices. Some of these boards are controlled from a central point over telegraph circuits; others are operated locally from keyboards installed in each broker's office. One type of board is designed to display the last dozen or more sales so as to indicate the trend of the market.

On May 21, 1929, the first Teleregister type of automatic stock quotation board was placed in service.in a broker's office in New York City. Since that time the demand for this service has been so great that within nine months approximately 20 per cent of the board rooms in New York City were receiving automatic service of some form.

With this particular type of equipment, all boards in a city or in a zone which may have a radius of several hundred miles are operated from a central transmitting station.

Mechanical Conveyers for Telegrams

A new type of conveyer wherein the telegram is carried on its edge on a moving belt in a narrow trough has been developed by the Western Union Telegraph Company for collecting telegrams from operating positions in large offices. This conveyer is called a "V Belt Conveyer" and takes its name from the shape of the trough in which the messages are carried. The belt runs along the back edge of the operating table and is readily accessible to the operator for depositing received telegrams thereon; a series of V belts carry the telegrams to a central point where the messages are routed to outgoing wires.

Municipal and Protective Signaling

There has been considerable extension of electrical traffic signals. The newer devices show a decided shift toward the "New Jersey" cycle, green, amber, red, green.

In congested districts there has been a considerable increase in progressive signals. With these a vehicle starting at one end of a street protected with a green light may travel through to the end without being delayed by a red light provided speed is kept within predetermined limits. There has also been a considerable increase in signals controlled by the vehicle. These are set to show green normally on the more traveled route and are reversed by vehicles running over a switch or magnet in the street. These have not yet been made satisfactory for congested districts since they do not make suitable provision for pedestrians, but improvements are being made to overcome this and other disadvantages.

The most important change in municipal fire alarm systems during the past year is a tendency to adopt improved current supply arrangements. One such type of arrangement is the single battery with trickle charger using copper oxide rectifiers or similar charging devices in place of duplicate batteries charged alternately by motor generators. Another type of improvement is the sealed type storage cell which is rapidly replacing the loose top cell. Similar improvements are being adopted for police signal systems.

The use of telephone typewriter systems by police organizations has gained headway. There are more than ten such systems now in service, including installations for the New York City police organization and the Pennsylvania State Police, each containing as many as 100 telephone typewriter stations.

Television

During the year there has been extensive progress in fundamental development.

This has included work on the application of television both to wire and radio systems. Television in colors was first demonstrated last June over a short wire circuit. This employs a new type of photo-electric cell responsive to all the colors of the visible spectrum, an improvement on the former type, which was sensitive only at the blue-green end. Special argon tubes combined with neon tubes previously used, together with color filters and new arrangements of apparatus, are employed. Moving as well as stationary objects can be clearly seen in their natural colors.

Sound Pictures

The growth in the use of sound picture systems in theaters continued and sound projection equipment is now universally applied in important motion picture theaters In the recording field improvements have been made in sound quality as the result of improved pickup devices, by refinements of electrical circuits, by better optical systems in the case of film recording, and refinements in photographic processes for handling films. Rerecording has become quite general in studio practise and special rerecording equipment has been developed. Both disk and film methods of sound recording continue in favor with the producers.

In projection, improvements in sound quality have resulted from improved optical systems and pick-up devices, and improved loudspeakers and driving mechanisms generally. Acoustic treatment of theaters to

secure better conditions for sound projection in theaters are found to be substantially different from those for direct audition in assembly halls.

A paper describing the technique and apparatus of sound picture recording and reproduction entitled *The Electrical Engineering of Sound Picture Systems* was presented at the Pacific Coast convention, at Santa Monica, California, September, 1929, by Messrs. K. F. Morgan and T. E. Shea.[1]

Foreign Telephone and Telegraph Matters of Interest

While the Communication Committee has made no complete record of communication developments in other countries, the following items which have been brought to the attention of the Committee are believed to be of interest:

In Europe, in 1929, 25 new international long-distance circuits were put into service between places not previously connected with each other. In some cases, there were services between two cities, in other cases between some principal city in one country and numerous cities in another country, and in other cases, numerous cities in two countries. This, the most rapid expansion of international long distance telephony which has ever taken place in Europe in one year, was made possible by the underground cables which have been laid within the last four years, during which period the number of important European cities connected internationally increased from 17 in 1925 to 76 up to the middle of 1929. The increase in service has been accompanied by a corresponding improvement in quality of transmission, and in density of traffic.

The Anglo-Polish service was extended into Poland to Cracow, Lodz, Poznan, and other towns. The Lodz exchange was connected by long distance with the Swiss telephone system. Nine additional departments of France were given telephone service with Switzerland so that the whole of that country, with the exception of Corsica, is now connected with the Swiss network. In addition, telephone communication between Copenhagen, Genoa, Milan, and Turin has been established via Switzerland.

1. A. I. E. E, Trans., Vol. 49, January 1930, pp. 105-116.

Telephone service between Great Britain and Finland, Paris and Finland, Rome and London, Switzerland and Italy, Hungary and Denmark, and Hungary and Poland is now available. Service between Stockholm and Reval, Esthonia, via Helsingfors, Finland, has also been established.

In October, 1929, telephone service was opened between two of the Canary Islands (Gran Canaria and Teneriffe) over a submarine cable nearly 40 nautical miles in length. This is a single-core, non-loaded cable with a copper tape return and is designed for the ultimate operation of six two-way carrier telephone channels in addition to the voice frequency channel and a direct-current telegraph circuit. The cable is in some places nearly 2 miles below the surface of the ocean.

A 20-nautical-mile telephone cable was laid between Algeciras, Spain, and Ceuta, Morocco, to supplement the cable placed between these points in 1924. This cable is designed for one telegraph circuit, one voice frequency telephone and six carrier telephone channels.

A 12-quad non-loaded cable, 37 nautical miles in length, was placed between Buenos Aires, Argentina, and Colonia, Uruguay. This cable is operated on a 4-wire basis in connection with 2-wire open-wire circuits from Colonia to Montevideo. The pairs have been equalized to 5000 cycles which has made it possible to secure very satisfactory results in broadcasting from Montevideo opera and other programs given at Buenos Aires.

In September, the new underground Paris-Lyon-Marseilles telephone cable was opened for service. It is 800 km. long and contains 130 circuits. In October, the new Italian underground cable linking Naples with Florence was inaugurated. The year also saw the underground telephone cable between Vienna and Graz extended to the Jugoslavian frontier, and the new East Prussian submarine cable laid between Leba and Pillau.

The Czechoslovakian Government during the year placed an order for a 120-kw. broadcasting station at Prague. So far as is known, this is the largest station which has been planned up to the present time in Europe.

Electrical Machinery

ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY*

To the Board of Directors:

The Committee on Electrical Machinery takes pleasure in submitting the following report on its work during the past year. The report is divided into two sections, the first dealing with organization and policies, and the second with the progress of the art.

Part I.—Organization and Policies

The Electrical Machinery Committee is organized with five permanent subcommittees, with the following memberships:

SUBCOMMITTEE ON SYNCHRONOUS MACHINERY

S. L. Henderson, Chairman, B. L. Barns, C. M. Gilt, C. F. Harding, J. A. Johnson, H. C. Louis, O. K. Marti, A. M. Rossman, O. E. Shirley, R. B. Williamson.

SUBCOMMITTEE ON TRANSFORMERS

V. M. Montsinger, Chairman, Raymond Bailey, W. H. Cooney, W. M. Dann, J. A. Johnson, H. C. Louis, J. H. Paget, J. F. Peters, Philip Sporn.

SUBCOMMITTEE ON INDUCTION MACHINES

H. B. Dwight, Chairman, A. B. Craig, J. L. Hamilton, C. J. Koch, F. Miller, C. A. Price, O. C. Schoenfeld.

SUBCOMMITTEE ON D. C. MACHINES

H. L. Zabriskie, Chairman, J. Bourath, J. L. Burnham, H. B. Dwight, Jesse B. Lunsford, A. M. MacCutcheon, E. P. Nelson, R. W. Owens, W. H. Powell, W. I. Slichter, J. G. Tarboux.

SUBCOMMITTEE ON MERCURY ARC RECTIFIERS

E. L. Moreland, Chairman, H. L. Andrews, L. D. Bale, A. E. Bettis, H. D. Braley, O. K. Marti, E. B. Paine, D. W. Proebstel, E. B. Shand, H. C. Sutton.

ANNUAL REPORT

C. M. Gilt.

The Committee has dealt with two principal subjects, standards and papers.

STANDARDS

During the year the Committee has studied many proposed changes in the existing A. I. E. E. Standards, and has recommended to the Standards Committee the adoption of alterations and additions relative to the following subjects or paragraph numbers:

Standard No. 5: D-C. Rotating Machines, Generators and Motors

A new definition of a two winding synchronous converter.

Revisions of paragraphs 5-356 (a) and 5-367 (a) relating to field rheostat losses.

Standard No. 7: Alternators, Synchronous Motors and Synchronous Machines in General

New definitions as follows:
Synchronous Reactance
Potier Reactance
Resistance Drop
Potier Reactance Drop
Potier Impedance Drop
Electrical Degree
Short Circuit Ratio
Terminal Voltage
Induced Voltage
Excited Voltage
Distortion Factor

A new paragraph relating to a method of calculation of field current at full load.

Revisions of paragraphs 7-457 (a), 7-461 (a), and 7-474 (a) relating to field rheostat losses.

Standard No. 9: Induction Motors and Induction Machines in General

New paragraphs relating to:
Allowable Voltage Unbalance
Definition of Breakdown Torque
Definition of Power Factor
Methods of Determining Power Factor

Revisions of:

Pars. 9-62	relating to slip
9-68	relating to definitions of protected machines
9-250	relating to break-down torque
9-301	footnote relating to conventional efficiency
9-310 (b)	relating to I^2R losses in the rotor
9-312	relating to brush contact loss
9-313	footnote relating to stray load losses.

Standard No. 13: Transformers, Induction Regulators and Reactors

Six new definitions of types of cooling.

Revisions of paragraphs 13-1, 13-215, 13-250, 13-400, 13-402, and 13-408.

Standard for Capacitors. A new standard for capacitors has been prepared and recommended to the Standards Committee for printing in report form.

The Committee desires very much to secure the early adoption of "American Standards" for all of the classes of electrical machinery, and its work on standards is all directed toward this end. At the present time, the only complete machinery standard, within the purview of this Committee, that has been approved as "American Standard" by the A. S. A. is that on synchronous

*COMMITTEE ON ELECTRICAL MACHINERY:
P. L. Alger, Chairman,
E. B. Paxton, Secretary,
L. F. Adams, B. L. Barns, W. M. Dann, H. B. Dwight, W. J. Foster, C. M. Gilt, W. S. Gorsuch, A. L. Harding, C. F. Harding, S. L. Henderson, L. F. Hickernell, J. Allen Johnson, H. C. Louis, A. M. MacCutcheon, O. K. Marti, L. W. McCullough, V. M. Montsinger, E. L. Moreland, F. D. Newbury, R. W. Owens, A. M. Rossman, R. B. Williamson, H. L. Zabriskie.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

converters, but the parts dealing with rating of Standards Nos. 5, 7, and 9 have also been approved as "American Standard." The complexity of the present organization for approving these standards, and the large number of interests that must be consulted before agreement can be secured, have made progress slow, but the recent organization of a new sectional committee on Rotating Electrical Machinery is expected to facilitate matters. This new sectional committee will be responsible for the preparation of "American Standards" on all types of rotating electrical machinery, and the Committee on Electrical Machinery is actively cooperating with it.

A number of questions in regard to standards of the International Electrotechnical Commission have been referred to the committee, and reports have been made to the Advisors on Rating of the U. S. National Committee of the I. E. C. Every effort is being made to promote agreement between the I. E. C. and the American Standards.

A series of test codes for induction, direct-current, and synchronous machines and transformers is under preparation by the Committee. These codes will give explicit directions for making performance tests on electrical machinery, so that electrical tests (especially those on combined equipments, such as waterwheel generators, motor driven pumps, etc.) can be performed in a uniform way.

Papers

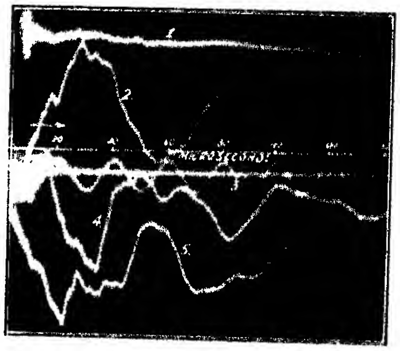
An important function of the Committee is to sponsor papers on electrical machinery, that will bring out discussion on new developments, and will properly record the progress of the art. During the past year, over 50 machinery papers have been submitted to the committee for review, and 34 have been actually presented at Institute Conventions, including twelve proposed for the 1930 Summer Convention.

There has been an increasing number of papers available during the past few years, and the need for more time for presenting, and space for recording, these papers is pressing. The Committee would like to sponsor symposiums on several aspects of electrical machinery developments during the next year or two, such as stray load losses, motor insulation, mechanical design, lightning protection of apparatus direct connected to transmission lines, reactance definitions and short circuit calculations, and mercury arc rectifiers. At the present time, the papers spontaneously submitted to the Institute occupy most of the available time at Conventions, so that there is little opportunity to develop such symposiums. The Committee, therefore, recommends that parallel sessions be held at conventions, that more papers be accepted for presentation, and that responsibility for abridging the papers and discussions to conform with the publication policies of the Institute be delegated to the committee chairmen.

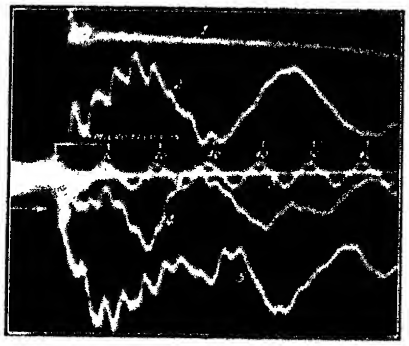
Part II—Resume of Progress of the Art

Transformers

Investigations into internal voltages in transformers have been actively continued during the year. The creation of high internal oscillations by lightning and switching surges of different kinds which were previously observed by sphere-gaps have been confirmed in the past year by the use of the cathode ray oscillograph. Fig. 1 shows oscillograms taken by the General



A



B

Fig. 1—Voltage Oscillations in Grounded Transformers

a. Core type b. Shell type

Wave No 1 Applied voltage
Wave No. 2 At point 50 per cent from neutral end of the winding
Wave No. 4 At point 26 per cent from neutral end of the winding
Wave No. 5 At point 78 per cent from neutral end of the winding
Wave No. 3 Timing

Electric Company on ordinary core and shell types of power transformers. Fig. 2 shows oscillograms taken by the Westinghouse Company on a 140-kv. shell type power transformer. Fig. 3 shows oscillograms taken by the General Electric Company on a power transformer of the non-resonating type.

The use of equipment for changing the ratio of transformers without interrupting the load has been extended and equipment for doing this has become largely standardized and manufactured on a quantity production basis. Improvements in simplicity and sturdiness have been made.

The recent development of the General Electric Company consists of three salient parts:

1. Two heavy ratio adjusters for 9 or 11 ratios with

an intermittent gear of high mechanical precision for turning first one and then another ratio adjuster to the next position.

2. Two oil-immersed, cam-operated contactors designed to remove the load from each ratio adjuster in succession during a change in ratio.

3. A motor operated driving mechanism including the position indicators, limit switch, and control devices.

All transformer connections are oil immersed and are so arranged that the reactance of the circuit is the same in all positions resulting in equal voltage steps. Simplicity with a minimum of connections outside the transformer tank have been the object of the design.

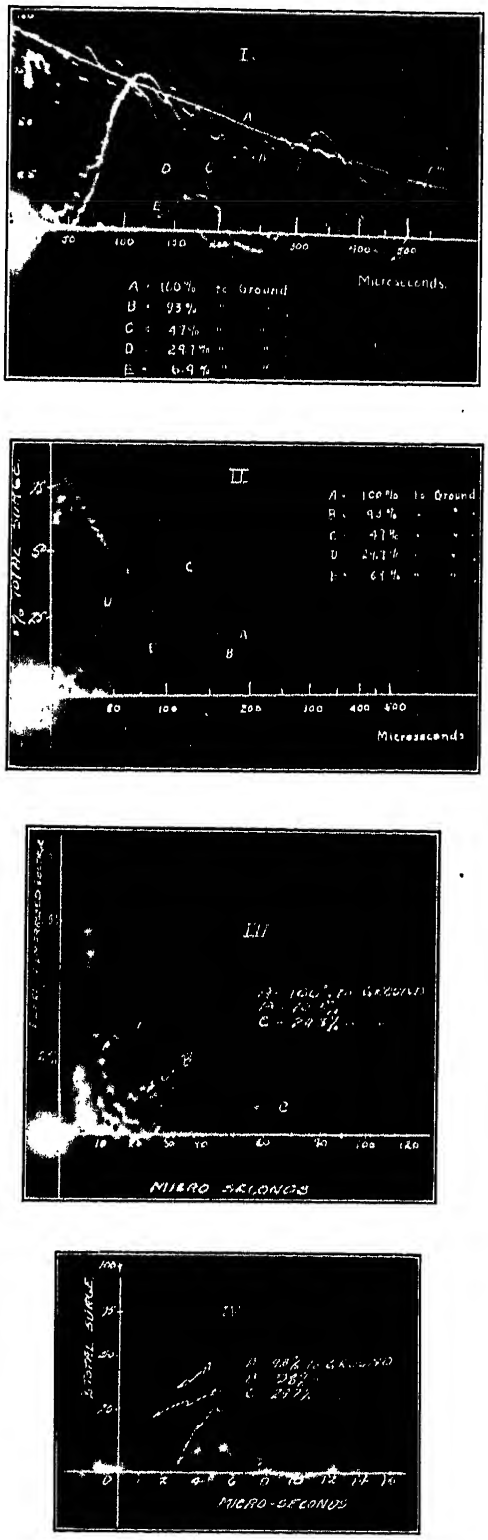


Fig. 2—Oscillograms Taken by the Westinghouse E. & M. Co. on a 140-Kv. Shell Type Power Transformer

I Oscillations with an extremely long wave
II Oscillations with a long wave
III Oscillations with a short wave
IV Oscillations with chopped surges

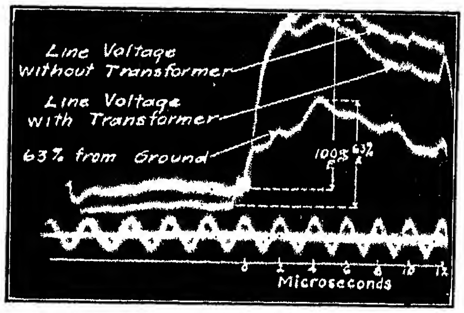


Fig. 3—Non-Resonating Transformer

1. Voltage wave at the end of transmission line with transformer disconnected.
2 Voltage wave at the end of the transmission line with transformer connected (voltage across transformer)
3. Voltage at 63 per cent point. Crest value 63 per cent of applied voltage
Note No. 3 a practical duplicate of the shape of No. 2 in spite of the fact that the transformer was out of oil and electrostatic unbalance was created thereby

Fig. 4 illustrates an interesting application of up-to-date load ratio control as applied to a 20,000-kv-a., single-phase, water-cooled transformer with two secondary windings. Each winding is equipped with load ratio control for supplying individual busses. There are six of these transformers installed by the Buffalo General Electric Company forming two 60,000-kv-a. banks which were supplied by the General Electric Company.

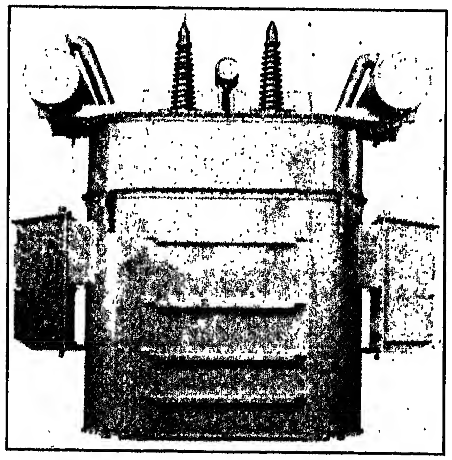


Fig. 4—A 20,000-Kv-a. Single-Phase Water Cooled, Load Ratio Control Transformer

Built by General Electric Co. for the Buffalo General Electric Co.

A difficult problem in load ratio control was met by

the Westinghouse Company by means of a separate regulating transformer and two of their UB tap changers and a reversing switch. The transformers are used for the operation of electrical furnaces, the largest of this type constructed in this country, and are rated 6500-kv-a. single-phase, 25 cycles, 12,000/45 volts with a low voltage current of 180,000 amperes at 1¼ load. By means of the load ratio control, the secondary voltage may be varied from 30 to 60 volts in steps of approximately ½ volt each.

The use of pothead transformers, in which cables are

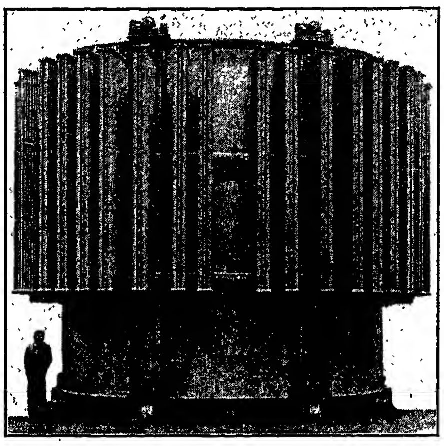


FIG. 5—A 60,000 KV-A. SINGLE-PHASE TRANSFORMER

Built by Westinghouse E. & M. Co. for the Roseland Switching Station of the Public Service Electric & Gas Co.

brought into a pothead without external bushings, has increased, and many potheads have been equipped with internally mounted disconnecting switches which were not designed to open the transformer exciting current. Recently, however, three transformers have been built by the Westinghouse Company for the Public Service Lighting Commission of the City of Detroit in which the potheads are provided with internally mounted disconnecting switches designed to interrupt the transformer exciting current. The transformers are rated 2000-kv-a., three-phase, 60-cycles, 24,000/600-volts.

A number of transformers have been built with two secondaries having a high reactance between them in order to minimize the effect of disturbances. An example of this is the 100,000-kv-a. General Electric auto-transformer now being built to be connected to a 12,500-volt generator on the primary side with two secondaries rated 24,500 Y. On account of the unbalanced load conditions that may exist, the equivalent two winding capacity is 58,000 kv-a.

Among the notable transformer installations of the year are four Westinghouse single-phase, 60-cycle units installed in Roseland Switching Station of the Public Service Electric and Gas Company. Each transformer has four separate windings rated at 30,000, 15,000, 15,000 and 20,000 kv-a., self-cooled. The design permits the addition of forced air cooling equipment to obtain 50 per cent higher ratings. On the basis of half the sum of these forced air-cooled ratings the units are equivalent to 60,000-kv-a., two-coil transformers. The windings are for connection to lines at 220,000 volts star, 132,000 volts star, 132,000 volts star, and 11,000 volts delta. The weight of each transformer as shipped is 270,000 lb. and was the heaviest individual unit shipped on a single railroad car.

During the year the maximum size of transformers for use with mercury arc rectifiers has shown considerable increase. A number of 3000-kw. units have been built and one of 6500 kw. for a 650-volt rectifier is now being constructed by the General Electric Company. A new method of compounding has been developed by this company which results in more desirable voltage characteristics and causes the rectifier to function at practically unity power factor at normal load.

Transformers grounded through reactors are subject to high voltages at the neutral when lightning or switch-

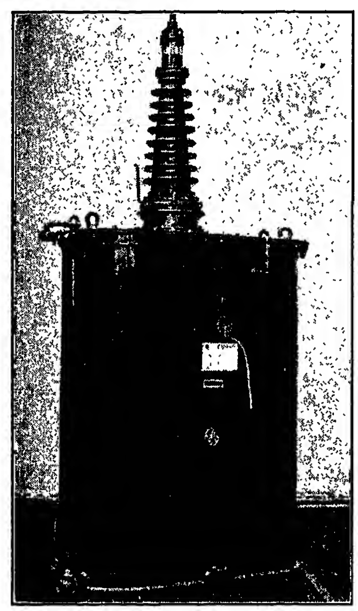


FIG. 6—NEUTRAL IMPEDOR

Developed by General Electric Co. to limit the voltage from transformer neutrals to ground

ing surges are applied to the line terminals. The General Electric Company has developed a grounding device called the "Neutral Impedor" for use with transformers when grounded with reactors or resistance. This device limits the voltage from neutral to ground to a predetermined value. In case such an impedor is used with a non-resonating transformer, the transient voltage distributes uniformly along the transformer winding. During the last year and a half nearly 800,000 kv-a. of transformers of non-resonating type have been built so that they can be operated with the impedor in the neutral.

Four 25,000-kv-a., 220-kv., single-phase transformers were recently shipped to the Southern California

Edison Company from the Westinghouse factory and are designed for grounding the neutral by means of a reactor. The design limits the maximum voltage of the neutral to 73 kv. above ground during a fault between line and ground. By the use of such a transformer and reactor the ground faults can be limited to a reasonably low value and the cost of installation is less than that required for transformers insulated for full voltage in both terminals.

Last year's report mentioned a standard single-phase "substation" designed for taking small power from a high-voltage line. Fig. 7 illustrates an expansion of the idea brought out by the General Electric Company to supply 150-kv-a., three-phase from a 110-kv. line.

The Brown Boveri Company has developed an interesting high-voltage potential transformer in which the core and coils are mounted in a hollow insulating bushing between a metal top and a grounded metal

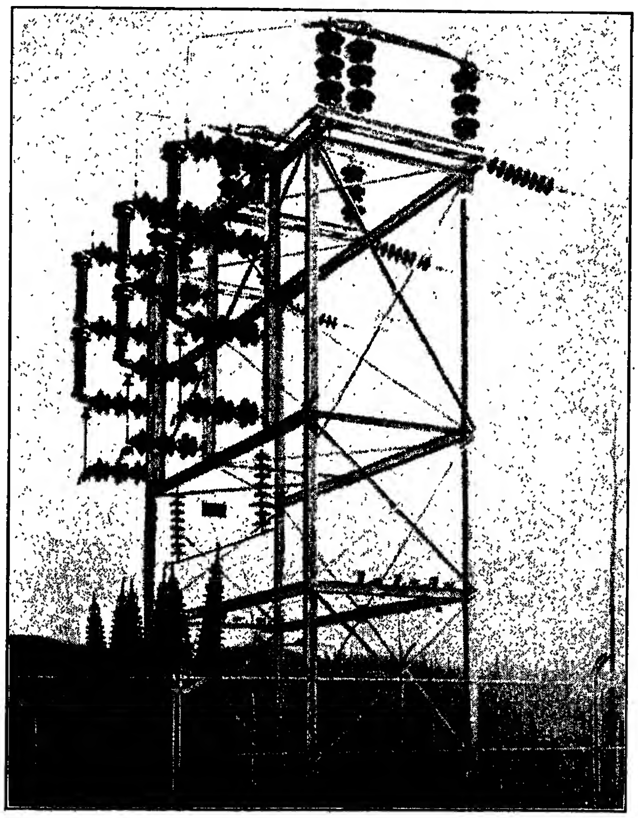


FIG. 7—150-KV-A. 110,000-VOLT THREE-PHASE UNIT DESIGN OUTDOOR STATION

With type RA-1 disconnecting switch, combined fusible cut-out and current-limiting resistor, three, 50-kv-a. single-phase transformers, low-voltage switch house and steel structure. View from side of tower.

bottom tank, with the primary leads connected to the cover and bottom tank.

An interesting metering transformer combination has been supplied to the Allied Power and Light Company by the Westinghouse Company for use on a 154-kv., 60-cycle system which consists of three double secondary transformers and a three-phase open delta connected voltage transformer. The extra current transformers

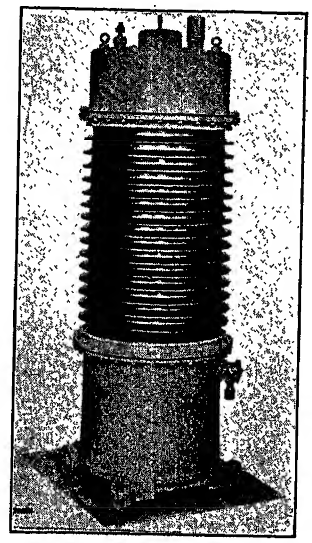


FIG. 8—150-KV. BROWN BOVERI POTENTIAL TRANSFORMER WITH INSULATION CASING

and double secondaries provide a double check and the potential transformer connection is equivalent to the use of a single-phase unit across two of the phases.

BIBLIOGRAPHY

ELECTRIC TRANSFORMERS

1929

1. Allan, J. C., "Recent Tendencies in Transformer Practise," *Pulp and Paper Mag.*, Internat. No., 1929, pp. 235-238.
2. Argersinger, R. E., "Advocates Simpler Voltage Ratings," *Elec. World*, Vol. 94, Nov. 16, 1929, p. 976.
3. Armstrong, C. A., "Power Transformers," *Power*, Vol. 68, October 30, '28, pp. 718-21; Vol. 69, Feb. 12, 1929, pp. 272-275.
4. Bailey, R., "Transformers and Regulators," *N. E. L. A. Bul.*, Vol. 16, Apr., 1929, pp. 232-233.
5. Bauhan, O., "Transport 72-Ton Transformers over Highway," *Elec. World*, Vol. 93, Feb. 2, 1929, p. 242.
6. Biskeborn, H. W., "Technical Progress in 1929," *Electrician*, Vol. 103, Dec. 27, 1929, pp. 787-8.
7. Blakeslee, T. M., "Tests Show Series Resistors Beneficial in Potential Transformer Circuits," *Elec. West.*, Vol. 62, Mar., 1929, p. 151,
8. Boyajian, A., "New Theory of Transformer and Autotransformer Circuits," *Gen. Elec. Review*, Vol. 32, Feb. 1929, pp. 110-19.
9. Brand, F. F. and Palueff, K. K., *Lightning Studies of Transformers by the Cathode Ray Oscillograph*, A. I. E. E. JL., Vol. 48, July, 1929, pp. 542-6.
10. Brand, F. F. and Stephens, H. O., "Some Economic Aspects Affecting the Design of Large Power Transformers," *Gen. Elec. Review*, Vol. 32, Nov. 1929, pp. 632-7.
11. Brooks, J. A., "Why Brooklyn Adopted Low-voltage A. C. Network," *Elec. World*, Vol. 94, Sept. 14, 1929, pp. 513-18.
12. Brosnan, T. J. and Kelly, R., *Developments in Network Systems and Equipment*, A. I. E. E. JL., Vol. 48, July, 1929, pp. 553-41.
13. Brown, R. L., "Electrical Characteristics of Auto-

Transformers," *Power Pl. Engng.*, Vol. 33, June 15, 1929, pp. 699-703.

14. Bucher, H., "Neue Formeln fur die Hauptabmessungen Eines Transformators, *Elektrotech. Zeit.*, Vol. 50, Sept. 5, 1929, pp. 1287-91.

15. Buell, H. H., "Transformer Loading and Load Measurement," *Elec. West.*, Vol. 62, May 15, 1929, pp. 485-8.

16. Burnham, L. H., "Methods of Cooling Power Transformers, *Power Pl. Engng.*, Vol. 33, Feb. 1, 1929, pp. 182-5.

17. Cameron, C. F., "Determining Full-Load Current on Single-Phase Transformers," *Ind. Engng.*, Vol. 87, Aug. 1929, pp. 410-11.

18. Camilli, G., "Testing of Transformers," *Gen. Elec. Review*, Vol. 32, Sept.-Oct., Dec. 1929, pp. 497-503, 566-70, 683-90; Vol. 33, Feb. 1930, pp. 115-22.

19. Chapman, P. E. and Brand, G. H., "Current Regulating Transformer Installation," *Elec. West*, Vol. 62, May 15, 1929, pp. 469-72.

20. Clark, G. D., "New Waterflow Indicator," *Electric Jour.*, Vol. 26, Dec. 1929, p. 568.

21. Clark, G. D., "Service Operation of Inertaire Transformers," *Elec. Jour.*, Vol. 26, Jan. 1929, pp. 18-21.

22. Clark, G. D. and Hagy, B. E., "Transformer Capacity Raised by Blast Hoods," *Elec. World*, Vol. 94, July 13, 1929, p. 56.

23. Craven, W. M., "Automatic Protection of Series Lighting Circuits," *Elec. World*, Vol. 93, June, 1, 1929, p. 1092.

24. Dalzell, D. R., "Correct Transformer Installation Insures Reliable Service," *Ind. Engng.*, Vol. 87, Feb. 1929, pp. 69-73.

25. Dalzell, D. R., "First-aids in Transformer Maintenance for Continuity of Service," *Ind. Engng.*, Vol. 87, Sept. 1929, pp. 458-61.

26. Danvers, W. K., "Transformer Installation Inspection," *Elec. World*, Vol. 94, Nov. 30, 1929, p. 1077.

27. Dodge, J. W., "Relay Protection for Power Transformers," *Gen. Elec. Review*, Vol. 32, May, 1929, pp. 268-72.

28. Edson, W. W., *Automatic Transformer Substations of the Edison Elec. Illum. Co. of Boston*, A. I. E. E. Jl., Vol. 48, June, 1929, pp. 440-444.

29. Ericson, R. C., "Transformer Impedances Reduced to Rated Values," *Elec. World*, Vol. 94, July 27, 1929, p. 180.

30. Evans, R. D. and Wagner, C. F., "Symmetrical Components; Determination of Phase Sequence Constants of Machines and Transformers," *Elec. Jour.*, Vol. 26, Dec. 1929, pp. 571-81.

31. Falk, L., "Kurzschlusspannung und Spannungsabfall in Dreiwicklungs-Transformatoren, Stromverteilung in Parallel Geschalteten Wicklungszweigen," *Elektrotech. Zeit.*, Vol. 50, Aug. 22, 1929, pp. 1231-6, 1265-9.

32. Gerber, H. L., "Centrally Located Transformer Vault Can Save Consumer Installation and Power Costs," *Elec. West*, Vol. 62, Jan. 1929, pp. 32-3.

33. Gibbs, J. B., "Constant Current Transformers on Three-Phase Circuits," *Elec. Jour.*, Vol. 26, Dec. 1929, pp. 569-70.

34. Hammerer, O., "Regeln fur Die Bezeichnung von Klemmen Beimaschinen Nebst Anlassern und Reglern sowie bei Transformatoren des VDE," *Elektrotech. Zeit.*, Vol. 50, Oct. 10, 1929, pp. 1475-8, 1497.

35. Hammerschmidt, W., "Beitrag zur Kenntnis der Ausguss Massen von Transformatoren," *Zeit. Angew Chem.*, Vol. 42, May 18, 1929, pp. 523-5.

36. Harder, D. C., "Protection Against Shock Necessary when Filtering Oil from Live Transformers," *Power*, Vol. 69, May 21, 1929, p. 834.

37. Hendricks, C. I., "Improved Transformer Vaults Used by the New Orleans Public Service, Inc.," *Elec. World*, Vol. 93, Jan. 26, 1929, pp. 189-90.

38. Hodgkinson, T. G., "General Solution for High Frequency Transformer and Oscillating Systems," *Electrician*, Vol. 103, pp. 241-3.

39. Hodnette, J. K., *Effect of Surges on Transformer Windings*, (Bibliog.), A. I. E. E. Jl., Vol. 48, Nov. 1929, pp. 829-32.

40. Hopp, A., "Mehrwicklungs-Transformatoren," *Elektrotech. Zeit.*, Vol. 50, June 13, 1929, pp. 865-6.

41. Howells, E. D., "Delta-Star, Three-Phase Transformers of Different Polarity can be Paralleled," *Elec. Jour.*, Vol. 26, Oct. 1929, p. 476.

42. Hruska, J. H., "Silicon Steel for Transformer Sheets," *Blast F. & Steel Pl.*, Vol. 17, Nov. 1929, pp. 1652-5.

43. Jansen, B., "Die Kuppelung und Unterteilung Grosser Netze Mit Hilfe von Regeltransformatoren," *Elektrotech. Zeit.*, Vol. 50, April 11, 1929, pp. 521-7.

44. Johnson, C. A., "Adapting Auto-Starters to Changed Conditions," *Ind. Engng.*, Vol. 87, Nov.-Dec. 1929, pp. 580-2, 641-3.

45. Kehse, W., "Uber den Begriff der Grossenkonstante im Transformatorenbau," *Elektrotech Zeit.*, Vol. 50, May 16, 1929, p. 711.

46. Kidder, A. H., "Surge Protection and Ground Resistance," *Elec. World*, Vol. 94, July 27, 1929, pp. 177-8.

47. Kramer, C., "Eine Neue Zwolfphasenschaltung von Transformatoren fur Grossgleichrichter," *Elektrotech. Zeit.*, Vol. 50, Feb. 28, 1929, pp. 303-5.

48. Lampbert, W., "Kann die Dritte Harmonische Unstabilitaten in Transformatorschaltungen Verursachen?" *Elektrotech. Zeit.*, Vol. 50, Jan. 24, 1929, pp. 117-20.

49. Langstaff, H. A. P., "Single-Phase Potential Transformers Rebuilt for Three-Phase Use," *Elec. World*, Vol. 92, Dec. 1, 1929, p. 1096.

50. Liston, J., "Some Developments in the Electrical Industry During 1928," *Gen. Elec. Review*, Vol. 32, Jan. 1929, pp. 43-4.

51. Lytle, J. A., "Improved Hatchway Design for Sidewalk Vaults," *Elec. World*, Vol. 94, Oct. 19, 1929, p. 780.

52. Macferran, M., *Parallel Operation of Transformers whose Ratios of Transformation are Unequal*, A. I. E. E. Jl., Vol. 48, Nov. 1929, pp. 809-12.

53. MacLeod, D. R., "New Equivalent Circuits for Autotransformers and Transformers with Tapped Secondaries, with some Examples of their Use in Analyzing Single-phase Three-wire A-C. Railway Systems," *Gen. Elec. Review*, Vol. 32, Feb. 1929, pp. 120-6.

54. McNeely, J. K. and McKee, E. R., "Design of Small Transformers," *Iowa State Col. Eng. Exp. Sta. Bul.* No. 87, '28, pp. 1-72 (bibliog. p. 35); Abstract, *Elec. World*, Vol. 92, Dec. 22, 1929, pp. 1242-3.

55. Merz, O., "Auswertung der Gemessenen Leerlaufverluste bei Transformatoren," *Elektrotech. Zeit.*, Vol. 50, Apr. 4, 1929, pp. 499-500.

56. Montsinger, V. M. and Wetherill, L., *Effect of Color of Tank on the Temperature of Self-Cooled Transformers under Service Conditions*, A. I. E. E. Jl., Vol. 48, Nov. 1929, pp. 821-5.

57. Montsinger, V. M. and Peters, J. F., "Surge vs. Impulse Tests for Transformers," *Elec. World*, Vol. 93, June 22, 1929, pp. 1275-7.

58. Newbury, F. D., "Electric Power Plant Equipment and Practise in America," *Elec. Jour.*, Vol. 26, Nov. 1929, pp. 508-12.

59. Norris, E. T., *Safe Loading of Oil-immersed Transformers*, A. I. E. E. Jl., Vol. 48, Aug. 1929, pp. 615-19.

60. Norris, E. T., "Thermal Rating of Transformers," *Inst. E. E. Jour.*, Vol. 66, pp. 841-54, (Bibliog. Aug. 1928) Discussion, Vol. 67, Jan. 1929, pp. 211-12.

61. Ogur, E., "Care of Transformer Installations in Industrial Plants," *Power Pl. Engng.*, Vol. 33, Mar. 1, 1929, pp. 297-9.

62. Pacific Coast Elec. Assn. Committee Report, "Maintenance of Distribution Transformers," *Elec. West.*, Vol. 62, May 15, 1929, pp. 418-26.

63. Paluoff, K. K., *Effect of Transient Voltages on Power Transformer Design*, A. I. E. E. Jl., Vol. 48, May 1929, pp. 357-61.

64. Peek, F. W., Jr., and Boyajian, A., "General Articles on Transformers," *Encyclopedia Britannica*, 14th Edition,

65. Read, E. K., "Circuit Breakers for Changing Taps on Transformers," *Power*, Vol. 69, Jan. 8, 1929, p. 59.

66. Reed, E. G., "Paper Insulation on Transformer Conductors Increases Quality," *Elec. Jour.*, Vol. 26, Nov. 1929, pp. 534-5.

67. Rich, T., "Refrigeration of Electrical Apparatus; Possibility of Using Pressure Gas Instead of Oil," *Elec. Review* (Lond.), Vol. 105, Nov. 22, 1929, pp. 887-8.

68. Rich, T., "Transformer Stations and Their Apparatus," *Electrician*, Vol. 102, Jan. 25, 1929, pp. 103-6.

69. Ritter, J. G. and Glenn, E. M., "New Hollow-Fin Transformer Tank," *Elec. Jour.*, Vol. 26, July 1929, p. 335-6.

70. Sanders, H. M., "High-Tension Metering; Features of Equipment Used on 220,000-Volt Lines for Measurement of Transfer Power," *Elec. World*, Vol. 94, Dec. 14, 1929, pp. 1168-9.

71. Schulze, H., "Neuerungen im Differentialschutz von Transformatoren," *Elektrotech. Zeit.*, Vol. 50, Aug. 15, 1929, pp. 1191-3.

72. Seelye, H. P., "Open Delta for Permanent Use," *Elec. World*, Vol. 93, Apr. 20, 1929, pp. 775-7.

73. Slavik, J., "Ein Neues Verfahren zur Bestimmung der Fehlergrossen bei Messwandlern," *Elektrotech. Zeit.*, Vol. 50, Sept. 19, 1929, pp. 1360-2.

74. Spilbury, R. S. J., "Precise Electrometer Method for Voltage-Transformer Testing," *Inst. E. E. Jour.*, Vol. 67, Sept. 1929, pp. 1143-6.

75. Stauffacher, E. R., "Establish Distribution Neutral with Grounding Bank," *Elec. World*, Vol. 93, Jan. 19, 1929, p. 153.

76. Stein, G., "Uber die Flussverteilung und der Zeitlichen Vorlauf der Magnetisierungsstrome in Drei und Funfschenlligen Drehstromtransformatoren," *Elektrotech. Zeit.*, Vol. 50, Aug. 15, 1929, pp. 1194-9.

77. Stephens, H. O., "Leakage Flux Distribution in Transformers with Concentric Windings," *Electric Light and Power*, October 1929, pp. 130-136.

78. Stigant, S. A., "Transformer Breakdowns," *Electrician*, Vol. 102, Jan. 4, 1929, p. 708; abstract with discussion; *Elec. Review*, (Lond.) Vol. 104, Jan. 11, 1929, pp. 85-6.

79. Stockton, F. H., "World's Largest Self-Cooled Transformer at United Electric Light and Power Co.," *Elec. Jour.*, Vol. 26, Feb. 1929, p. 88.

80. Taylor, W. T., "Electric Power System Development," *Electrician*, Vol. 103, Aug. 23, 1929, pp. 215-6.

81. T. R. E., 1930, "Regeln fur die Bewertung und Prufung von Transformatoren," *Elektrotech. Zeit.*, Vol. 50, May 30, 1929, pp. 794-806.

82. Weller, C. T., *132-kv. Shielded Potentiometer for Determining the Accuracy of Potential Transformers*, A. I. E. E. Jour., Vol. 48, April 1929, pp. 312-16.

83. Wiggins, A. M., "Improved Current Transformers with Nickel-iron Cores; Hipernik," *Elec. Jour.*, Vol. 26, April 1929, pp. 152-4.

84. Wiggins, A. M., "Nickel-iron Cores Improve Current Transformers," *Elec. World*, Vol. 93, Jan. 26, 1929, p. 188.

85. Wiggins, A. M., "Parallel Operation of Current Transformers for Totalizing Two or More Circuits," *Elec. Jour.*, Vol. 26, Aug. 1929, pp. 379-81.

86. Wilson, M. S., *New High-Accuracy Current Transformer*, A. I. E. E. Jour., Vol. 48, March 1929, pp. 179-82.

87. Wingo, A. C. and Allen, C. M., "Power Transformers Salvaged and Rebuilt," *Elec. West*, Vol. 62, April 1929, pp. 210-11.

88. Jost, I. A., "Transformers for Operating Series Incandescent Lamps," *Elec. Jour.*, Vol. 26, Dec. 1929, p. 587.

89. Anonymous, "Compact Transformer Platform," *Elec. World*, Vol. 94, Nov. 9, 1929, p. 936.

90. Anonymous, "Conveyance of Large Transformers," *Engineer*, Vol. 148, Sept. 13, 1929, p. 285.

91. Anonymous, "Developments in Electric System Practise," *Power Pl. Engng.*, Vol. 33, Dec. 15, 1929, pp. 1367-9.

92. Anonymous, "Economical Test-Box Installation," *Elec. World*, Vol. 93, May 18, 1929, p. 977.

93. Anonymous, "Electric Switching and Transmission; Tabulation," *Power Pl. Engng.*, Vol. 32, Dec. 15, 1929, pp. 1334-6.

94. Anonymous, "Emergency Transformer Paralleling Expedited by Predetermination of Load Division," *Elec. West.*, Vol. 63, Sept. 1929, pp. 128-9.

95. Anonymous, "Erie Extends Itself to Move Large Shipment," *Ry. Age*, Vol. 87, Sept. 14, 1929, p. 642.

96. Anonymous, "Grid Transformers," *Engineer*, Vol. 147, May 10, 1929, p. 526.

97. Anonymous, "High-Voltage Transformers; 132 Kv. Metrovick Transformers," *Elec. Review*, (Lond.) Vol. 104, May 10, 1929, pp. 820-1.

98. Anonymous, "Isolating Potential Transformers," *Elec. World*, Vol. 94, Dec. 21, 1929, p. 1223.

99. Anonymous, "Large Water-Cooled Transformers; a 33,000 Kv-a. 145,000 V Bank," *Electrician*, Vol. 103, Sept. 6, 1929, p. 270; *Elec. Review*, (Lond.) Vol. 105, Oct. 4, 1929, pp. 583-4.

100. Anonymous, "Mishap at Nechells," *Elec. Review*, (Lond.) Vol. 105, Dec. 13, 1929, p. 1067; *Electrician*, Vol. 103, Dec. 6, 1929, p. 712.

101. Anonymous, "Modern Switchgear and Transformers; Stafford Works of the English Elec. Co.," *Elec. Review*, (Lond.), Vol. 105, July 26, 1929, pp. 170-1; *Electrician*, Vol. 103, Aug. 2, 1929, pp. 135-6.

102. Anonymous, "Norwegian Hydro-Electric Station," *Elec. Review*, (Lond.), Vol. 105, Dec. 20, 1929, p. 1115.

103. Anonymous, "Operating Transformers on Other Than Normal Frequencies," *Electric Jour.*, Vol. 26, Dec. 1929, pp. 588-9.

104. Anonymous, "Pole Transformers," *Electrician*, Vol. 103, Sept. 27, 1929, p. 353.

105. Anonymous, "Reference Tables for Use in Routine Tests of Distribution Transformers," *Elec. West*, Vol. 62, pp. 216-17.

106. Anonymous, "Regulating a 30,000-Kv-a., 13,200-Volt Line," *Elec. Jour.*, Vol. 26, Nov. 1929, pp. 524-5.

107. Anonymous, "Shipping Large Transformers Presents Unusual Problem," *Elec. Jour.*, Vol. 26, Sept. 1929, pp. 438-9.

108. Anonymous, "Single-Pole Platform for Two Transformers," *Elec. World*, Vol. 93, May 4, 1929, p. 875.

109. Anonymous, "Super-voltage Measurement; the British Thomson Houston Co. Method," *Elec. Review*, (Lond.), Vol. 105, Nov. 29, 1929, pp. 967-8.

110. Anonymous, "Three-Phase 132-Kv. Transformers," *Elec. Review*, (Lond.), Vol. 104, Apr. 5, 1929, pp. 633-4; *Electrician*, Vol. 102, Apr. 5, 1929, p. 413.

111. Anonymous, "Transformer Tap-Changing on Load," *Engineer*, Vol. 148, July 12, Aug. 16, 1929, pp. 30-3, 56-7, 84-5, 110-12, 139-40, 176-8.

112. Anonymous, "132,000-Volt Transformers and Switchgear for the Gear," *Engineer*, Vol. 147, June, 1929, pp. 690.

113. Anonymous, "Visit to the British Thomson Houston Works," *Engineer*, Vol. 148, Nov. 29, 1929, pp. 573-6.

114. Anonymous, "Visit to the Stafford Works of the English Elec. Company," *Engineer*, Vol. 148, Aug. 30, 1929, pp. 221-4.

115. Anonymous, "World's Largest Transformers," *Power Pl. Engng.*, Vol. 33, Sept. 1, 1929, pp. 976-7.

Synchronous Machinery

The increasing use of fabricated construction of rolled and welded steel members has continued and is becoming more and more universal except for standardized designs in which duplicate castings are used in large quantities. The so-called "dished" steel-plate end-shields have been applied to several large synchronous motors, hydrogen-cooled condensers, and marine motors. The General Electric Company has developed a line of bearing pedestals to harmonize with the appearance of the fabricated construction and has modified the design of the oil wells so that the rings operate completely enclosed, practically eliminating the escape of oil vapor. The bearing construction has been modified to secure more uniform distribution of the pressure.

The year 1928 saw a large increase in the kv-a. capacity of water wheel generators while the size of turbo-generators stayed about the same. The past year has seen the reverse process in which the capacity of single shaft turbo-generators has been increased to 166,666 kv-a. The interest in outdoor rotating machinery has increased and several of this type have been built or are in the process of construction. The successful experience with hydrogen-cooled condensers has been continued and more machines of this type are under construction.

Hydraulic Generators. The following is a list of some of the more interesting hydraulic driven generators installed or being built during the past year:

Purchaser	No.	Kv-a.	Speed	Manufacturer
Dnieprostroy Hydroelectric Dev.	4	77,500	88.2 r.p.m.	General Electric
Sao Paulo Tramways	1	55,000	360 "	" "
New York Power and Light Co.	1	47,000	81.8 "	" "
Aluminum Co. of America	2	45,000	150 "	Westinghouse
Carolina Power & Light Co.	3	45,000	400 "	"
Lexington Power Company	4	40,625	138 "	"
New England Power Company	4	39,000	138 "	"
City of Seattle	1	33,000	257 "	"
Arkansas Power & Light Co.	2	31,111	94.7 "	Allis Chalmers
Portland Oregon Electric Power Co.	1	30,000	514 "	General Electric
City of Tacoma	2	30,000	300 "	Allis Chalmers
Alabama Power Co.	2	29,000	100 "	Westinghouse
Central Maine Power Co.	2	26,667	138.5 "	General Electric
Montana Power Co.	2	25,000	81.8 "	Westinghouse

The 55,000-kv-a., 360-rev. per min. machine which is being built by the General Electric Company is the largest horizontal water-wheel generator which has been built up to the present time. The 47,000-kv-a., 81.8-rev. per min. generator is a vertical unit of the over-hung type with the guide and thrust bearings located together beneath the rotor.

The machines for the Lexington Power Co., New England Power Co., and the Montana Power Co., built by Westinghouse are all of the over-hung type.

The 31,111-kv-a. generator being built by the Allis Chalmers Company is also the over-hung type. The stator is of welded plate and the rotor spider is made of cast steel in four segments. The poles are bolted to the spider and the arms are shrouded to reduce windage loss.

The Brown Boveri Company has built a vertical 20,000 kv-a., 250-rev. per min. machine which is particularly interesting in that it is capable of supplying the same rated output at either 50 or 16⅔ cycles at the same speed. When operating to produce 50 cycles, the spider is provided with 24 poles dovetailed into one slot each and when delivering 16⅔ cycles there are 8 poles fitting two dovetails with an empty slot between each two poles.

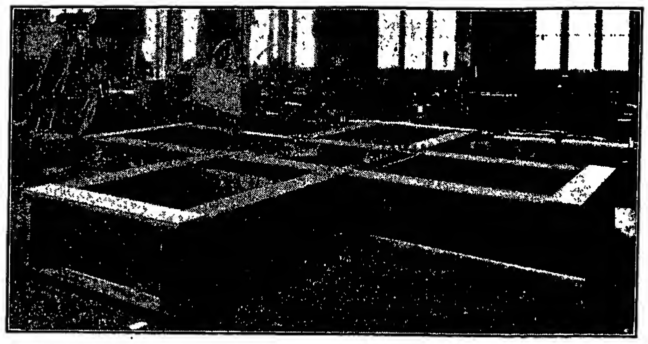


Fig. 9—Upper Bearing Bracket of 77,500-Kv-a. General Electric Water Wheel Generator for Dnieprostroy Hydro-Electric Development, Russia

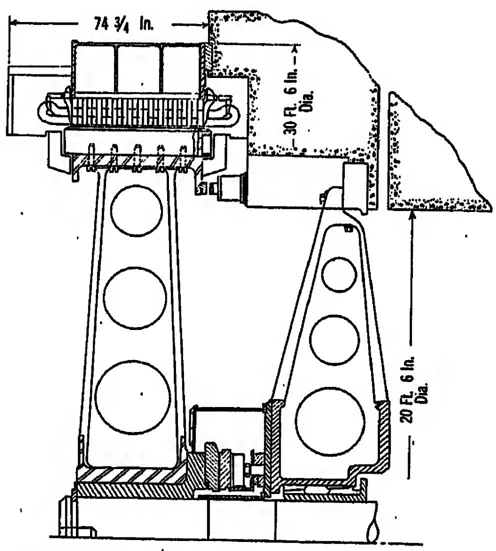


Fig. 10—Cross-Section Sketch of Allis Chalmers Co's. 31,111-Kv-a. Overhung Type Hydraulic Machine

Built for Arkansas Power & Light Company

Steam Turbine Generators. The size of single shaft units has increased until now the General Electric Company is building a 166,666-kv-a., 1800-rev. per min., single-shaft turbo-generator for the State Line Generating Company and the 160,000-kv-a., 1500-rev. per min., 25-cycle, single-shaft, turbo-generator built by the same company is operating in the East River

station of the New York Edison Company. The 235,000-kv-a., three-shaft generator at the State Line Plant at Chicago was placed in operation during the year.

The Allis Chalmers Company is building a 115,000-kw., 18,000-volt, 1800-rev. per min., single-shaft generator for the Waukegan Station of the Public Service Company of Northern Illinois. The rotor is a single forging and is one of the largest yet undertaken; rough-turned; the weight is 240,000 lb. On these extremely large, long generators, external motor driven fans are being used so as to keep the span between the bearings as short as possible.

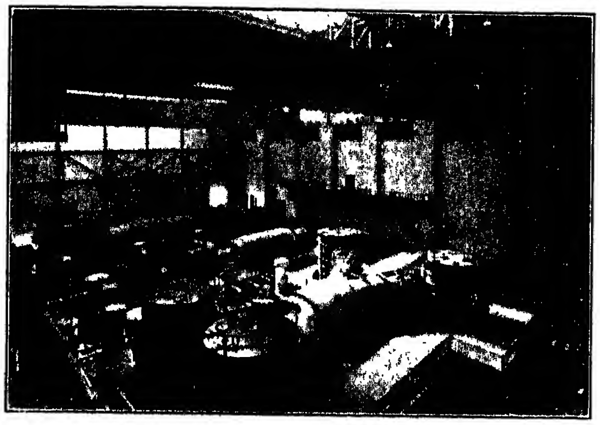


Fig. 11—235,000-Kv-a. Three-Shaft Generator
Built by the General Electric Co. for the State Line Plant of Chicago

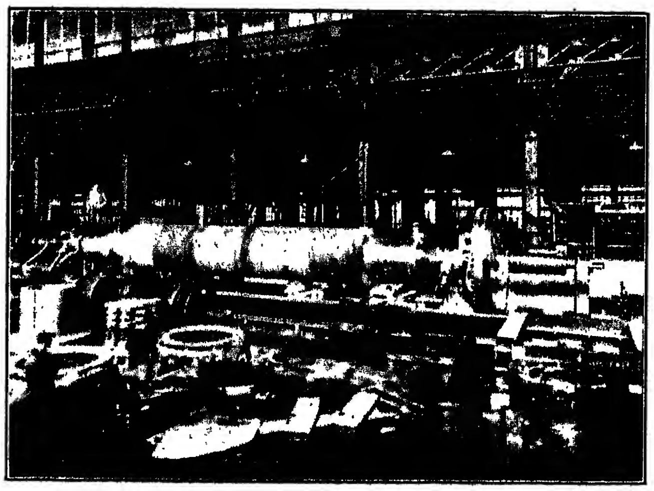


Fig. 12—240,000 Lb. Single Forging for the 115,000-Kw. Generator Rotor Being Built by the Allis Chalmers Co.

An interesting development in turbo generators has been the vertical compound type of installation developed to reduce floor space. The largest of these is that installed at the Ford Motor Company consisting of two units, each running at 1800-rev. per min. with a total capacity of 124,911 kv-a. Two units of this type are being furnished the Pacific Gas and Electric Company by the General Electric Company in which the low pressure unit operates at 1800-rev. per min. and the high pressure at 3600-rev. per min. and with a total capacity of 50,000-kv-a. Two similar machines are being furnished the Jersey Central Power and Light Company by the General Electric Company with a total capacity of 31,250 kv-a.

The Westinghouse Company has increased the size of 3600-rev. per min. units to 18,750 kv-a. Three of these machines are being built for the Louisiana Steel Products Company and two for the Virginia Public Service Company. These generators are equipped with special propeller type fans mounted on the shaft.

The Westinghouse Company has been able to make an interesting factory test on two duplicate turbo generators of 68,800-kv-a. capacity built for the Duke Power Company. The test included a "pump-back" loading at 0.8 power factor full load and substantiated the present A. I. E. E. Standards which use the short circuit losses as equivalent to the load losses at full voltage and full load.

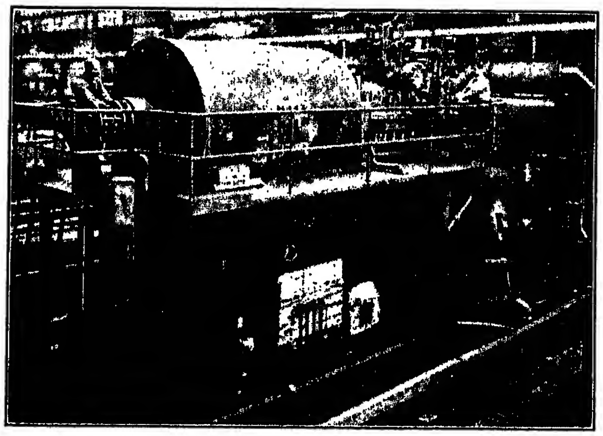


Fig. 13—25,000-Kw. General Electric Vertical Compound Steam Turbine Generator for the Jersey Central Power & Light Co., Being Assembled for Test

Voltage of 22,000 has thus far proved efficient, and there are five General Electric generators at this voltage which have been in successful operation for periods varying from several months to one and one-half years. Two 116,600-kv-a. and one 166,666-kv-a. generators are being built for 22,000 volts.

The use of the double winding generator is being extended and there are now 768,333 kv-a. of double winding generators of General Electric manufacture in operation or in the course of construction.

Synchronous Motors. The use of synchronous motors has been extended to include band saws, fans and blowers, and flour mills. The General Electric Company is now building one 3000-hp., 124-rev. per min., compressor motor which is believed to be the largest motor for this service undertaken so far. The two largest diameter synchronous motors are 25 ft.

in diameter and are supplied by the Westinghouse Company to the Columbia Steel Company for driving a billet mill and a sheet bar mill. The motors are rated 5000 hp., 82 rev. per min. at 2300 volts and when started at full voltage the starting torque is 95 per cent

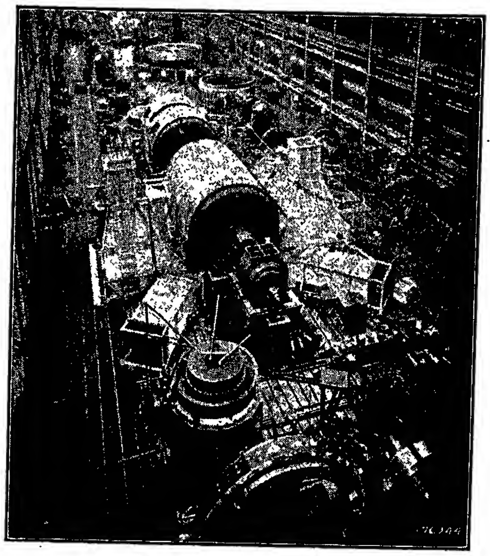


FIG. 14—VIEW IN WESTINGHOUSE SHOPS SHOWING "PUMP BACK" TEST OF TWO DUPLICATE GENERATORS OF 68,800 KV-A. CAPACITY

with 330 per cent current in-rush. The torque of pull-in is 40 per cent and the pull-out is 220 per cent. The Westinghouse Company is building an 1800-hp., 150-rev. per min. motor for a piercing mill of a seamless tube

FIG. 15—THE LARGEST DIAMETER SYNCHRONOUS MOTOR. IT DRIVES A SHEET BAR MILL FOR THE COLUMBIA STEEL CO.

plant which develops a pull-out torque at 350 per cent of normal load.

There seems to be an increasing demand for high speed synchronous motors and the Allis Chalmers Company has recently built a 500-hp., 3600-rev. per min. motor for driving a pump. The construction of this is similar to that of a turbo generator except for special features to provide adequate starting.

The General Electric Company has built some synchronous motors with two circuits, one of which is left open when starting, to reduce the starting current when started at full voltage.

Dynamic braking has been applied for reducing the time of stopping. Some applications have been made in which the field circuit has been connected single circuit for running and two circuits parallel for stopping, giving the equivalent of double excitation during the braking period.

The Allis Chalmers Company has built a number of synchronous induction type motors for cement mill drive which give the advantage of high starting current and moderate line current during the starting period without clutches and give the advantages of the synchronous motor under normal running condition.

Marine Synchronous Motors. During the year the *SS. Pennsylvania* joined the *SS. Virginia* and *SS. California* in commercial operation. These 18-knot

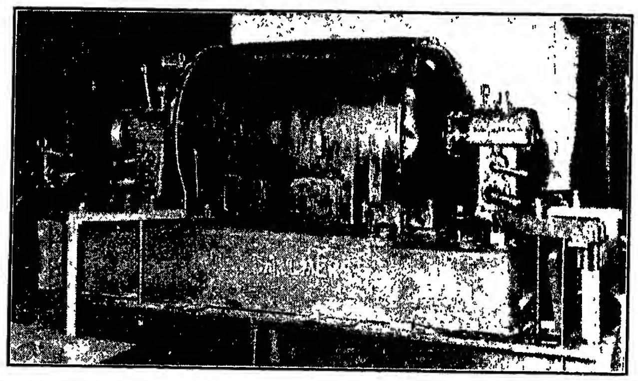


FIG. 16—A 500-HP., 3600 REV. PER MIN. SYNCHRONOUS MOTOR BUILT BY THE ALLIS CHALMERS CO.

vessels are each propelled by two 8500-hp., 120-rev. per min., self-starting synchronous motors. The Grace Line *SS. Santa Clara* was launched and will be equipped with two 6300-hp., 120-rev. per min., self-starting synchronous motors to drive the ship at 19 knots. Four 8000-hp., 143-rev. per min., self-starting synchronous motors were completed for the two Ward ships, *SS. Oriente* and *SS. Morro Castle.* The above equipment was furnished by the General Electric Company. Two ships are being built for the Dollar Line which will be the largest and highest powered of any ships built in the country for commercial service with electric drive. The General Electric Company will furnish the two 13,250-hp. synchronous motors for one ship and the Westinghouse will furnish the same drive for the other.

Synchronous Condensers. The Westinghouse Electric and Manufacturing Company have on order a 15,000-kv-a., hydrogen-cooled condenser for the Indiana and Michigan Electric Company and a 15,000-kv-a., hydrogen-cooled machine for the

Southern California Edison Company. The General Electric Company is building a 15,000-kv-a., 900-rev. per min., 24,000-volt, hydrogen-cooled condenser for the American Gas and Electric Company. There are now 32,500 kv-a. in hydrogen-cooled condensers of General Electric manufacture in opera-

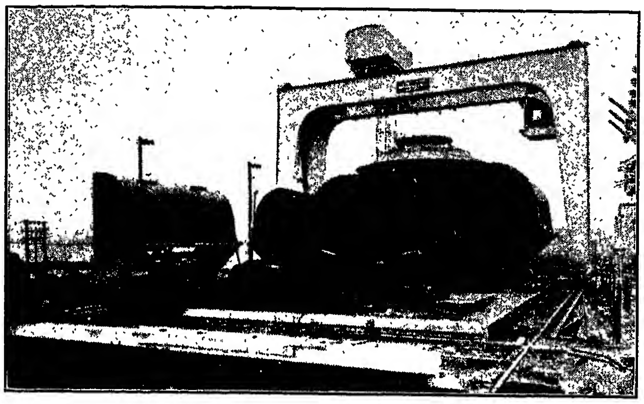


FIG. 17—THE FIRST OF TWO 25,000 KV-A., 500-REV. PER MIN. OUTDOOR CONDENSERS

Furnished the Toronto Leaside Station by the Canadian Westinghouse Co.

tion and 75,000 kv-a. in construction. The largest size condensers now under construction include a 30,000-kv-a., 600-rev. per min. machine for the Public Service Electric and Power Company of New Jersey, a 30,000-kv-a., 600-rev. per min., 60-cycle unit for the Southern California Edison Company, being

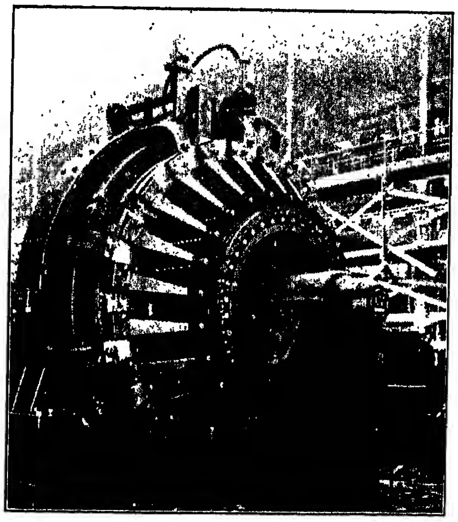


FIG. 18—3900-KW., 13,000 AMPERE ROTARY CONVERTER

Being built by Westinghouse Elec. & Mfg. Co. for Commonwealth Edison Co. of Chicago

built by the General Electric Company, a 30,000-kv-a., 720-rev. per min. synchronous condenser being built by the Allis Chalmers Company, and one at 720-rev. per min. and two at 600 rev. per min. of the same capacity constructed by Westinghouse.

The Canadian Westinghouse reports the installation of two 25,000-kv-a., 500-rev. per min. vertical outdoor synchronous condensers at the Toronto Leaside transformer station of the Hydro-Electric Power Commission of Ontario. These machines are of particular interest in that they are the first vertical shaft outdoor type condensers with the exciters suspended below the thrust bearing, which is located under the rotor.

Frequency Converters. The Westinghouse reports the installation of a second 40,000-kv-a. frequency changer of the synchronous-synchronous type for the Commonwealth Edison Company. The same manufacturer is building an 18,750-kv-a., 300-rev. per min. set for the Consumers Power Company to act as a tie-in between a 30-cycle and a 60-cycle system. It is expected that at a later date the machines may be split and each one used as a 60-cycle condenser. The 30-cycle end will then be operated with a rating of 35,000-kv-a. at 600 rev. per min.

The Toledo Edison Company has placed in operation a 35,000-kw., 300-rev. per min. General Electric synchronous-synchronous set having a 46,000-kv-a., 60-cycle, 13,500-volt motor and 41,176-kv-a., 25-cycle, 6750-volt generator.

BIBLIOGRAPHY

SYNCHRONOUS MACHINES

G. W. Penney, *Short Circuit Torque in Synchronous Machines without Damper Windings*, A. I. E. E. TRANS., Vol. 48; Oct. 1929, pp. 1230-40.

R. E. Doherty and C. A. Nickle, *Three-Phase Short-Circuit Synchronous Machines*, A. I. E. E. TRANS., Vol. 49, Jan. 1930, pp. 38-41.

C. A. Powel, "An Elementary Conception of Stability," *Electric Journal*, June 1929, pp. 279-282.

C. F. Hill, "Corona Eliminated in High-Voltage Generators," *Elec. World*, Jan. 19, 1929, pp. 139-140.

C. A. Parsons and J. Rosen, "33,000-Volt Generators Save $172,000 in 75,000-Kw. Plant," *Elec. World*, Nov. 9, 1929, pp. 932-935.

L. C. Snively, "Synchronous Reactance Measured with Machine in Use," *Elec. World*, Dec. 28, 1929, p. 1285.

L. F. Hunt, "Minimizing Fault Damage Within Generators," *Elec. World*, Dec. 28, 1929, pp. 1263-1265.

T. F. Barton, "The Double-Winding Generator," *General Electric Review*, June 1929, pp. 302-308.

"Electric Equipment," *Power*, Jan. 1, 1929, pp. 14-15.

W. Jackson, "Transient Phenomena During Alternator Short Circuits," *World Power*, Aug. 1929, pp. 135-137.

A. St. C. Dunstan, "Auburn Professor Investigates Breakdown of Generator," *Auburn Engr.*, Jan. 1929, pp. 5, 16, 18-20.

J. C. Prescott, "The Free Period of Coupled Alternators," *Inst. Elec. Engrs.* (Lond.), Jan. 1929, pp. 141-148.

G. E. Taylor, "Reverse-Power Alternating Current Relays for 3-Phase Generator and Feeder Protection," *Inst. Elec. Engrs.* (Lond.), Jan. 1929, pp. 210-211.

G. J. T. Bakker and J. C. Van Staveren, "Insulation of Large High Tension Synchronous Generators," *Electrician* (Lond.), June 21, 1929, pp. 749-750.

C. Parsons and J. Rosen, "Direct Generation of Alternating Current at High Voltages, *Engineer* (Lond.), Mar. 22, 1929, pp. 321-322; *Elec. News* (Toronto), Apr. 15, 1929, pp. 44-46; *S. African Engr.* (Johannesburg) May, 1929, pp. 21-25; June 1929, pp. 17-20.

A. A. F. Giles, "Alternator Protection," *Elec. Rev.* (Lond.), Sept. 6, 1929, pp. 388-391.

G. Haynes, "Synchronous Frequency Changers," *Elec. Times* (Lond.), Aug. 15, 1929, pp. 235-336.

T. W. Ross and M. Kaufmann, "The Protection of Alternating Current Generators," *M-V Gazette* (Manchester), Mar. 1929, pp. 212-217; Apr. 1929, pp. 245-251; May 1929, pp. 262-266; June 1929, pp. 297-301.

R. David, "Short Circuit of Alternators," *Rev. Gén. Elec.*, May 25, June 1 and 8, 1929, pp. 795-810, 840-850, 883-890.

T. Lehmann, "Formulas Permitting Calculation of Permeance Between Rounded Pole with Various Radii of Curvature and Cylindrical Armature Smooth or with Teeth," *Rev. Gén. Elec.*, Sept. 28 and Oct. 5, 1929, pp. 477-484, 521-528.

L. Guyon, "New Alternator of 50,000 Kw. of Generating Plant at Gennevilliers of l'Union d'Electricité," *Rev. Gén. Elec.*, Nov. 2, 1929, pp. 705-719.

P. H. E. V. Dooren, "Voltage Regulation and Over Current Protection of 3 Phase Generators," *Ingenieur* (The Hague), Aug. 10, 1929, pp. E. 101-E. 107

Schwenkhagen, "Buchholz Protection for Generators," *Elektroteknisk Tidskrift* (Oslo), Aug. 5, 1929, pp. 303-305.

A. O. Hals, "Potential Waves in Voltage Curve of Synchronous Generators," *Elektroteknisk Tidskrift* (Oslo), Oct. 5, 1929, pp. 443-446.

D. D. Chase and H. C. Forbes, "Electric Generators of Double Winding," *Ingenieria International*, Mar. 1929, pp. 112-113.

M. Urushibata S. Yamada, "On the Experiment of Sudden Short-Circuit Current of Large Alternators," *Inst. Elec. Engrs. of Japan-Jl.*, Jan. 1929, pp. 103-118.

S. Yamada and M. Urushibata, "On the Experiment of Sudden Short-Circuit of Large Alternators," *Inst. Elec. Engrs. of Japan-Jl.*, Jan.-Feb. 1929, pp. 20-23.

M. Terai, "On the Parallel Operation of Synchronous Machines Driven by a Diesel Engine and a Steam Turbine," *Inst. Elec. Engrs. of Japan-Jl.*, Aug. 1929, pp. 870-878.

S. Ozawa, "Generation of Low Frequency Power," *Inst. Elec. Engrs. of Japan-Jl.*, Aug. 1929, pp. 879-896.

S. Ozawa, "Low Frequency Single Phase Compound Generator," *Inst. Elec. Engrs. of Japan-Jl.*, Sept. 1929, pp. 1007-1023.

H. Schwenkhagen, "Buchholz Protection for Generators," *E. T. Z.*, July 11, 1929, pp. 1016-1018.

H. Schwenkhagen, "Performance of Buchholz Protection in Case of Generator Trouble," *E. T. Z.*, Nov. 14, 1929, pp. 1649-53.

R. Willheim, "Three-Phase Current Generators without Cross-Field Damping as Elements of Resonance Circuits," *Archiv. fuer Elektrot.*, Apr. 8, 1929, pp. 593-611.

J. Schammel, "Symbolical Analysis of Current Diagram of Synchronous Machine with Salient Pole," *Archiv. fur Elektrot.*, Nov. 19, 1929, pp. 237-257.

A. Mandt, "Characteristic Values for the Permanent Short Circuit in Three Phases and Sudden Short Circuit of the Synchronous Machine," *E. u. M.*, July 7, 1929, pp. 569-573.

B. Gerstmann, "Synchronous vs. Asynchronous Alternating Current Railroad Motor," *E. u. M.*, Sept. 1, 1929, pp. 720-735.

V. Schaubert, "Protective Equipment with Range Limited by Current Limiters," Fachberichte der XXXIV Jahresversammlung, des *Verbandes Deutscher Elektrotechniker* (Aachen), 1929, pp. 33-35, and disc. pp. 35-36.

Modern Method of Stator Winding," *A. E. G. Progress*, Dec. 1929, pp. 378-383.

W. Peters, "New Method for Synchronizing Electric Machinery and Power Plants," *Siemens Zeit.*, Mar. 1929, pp. 163-175; Apr. 1929, pp. 240-251.

E. J. Burnham, J. R. North, and I. R. Dohr, *Quick Response Generator Voltage Regulator Field Tests Made with Oscillograph*, A. I. E. E. Trans., Vol. 48, July 1929, pp. 903-909.

C. M. Laffoon and J. F. Calvert, *Iron Losses in Turbine Generators*, A. I. E. E. Trans., Vol. 48, July 1929, pp. 856-871.

W. J. Foster and M. A. Savage, *Design Features that Make Large Turbine Generators Possible*, A. I. E. E. Trans., Vol. 49, Jan. 1930, pp. 60-67.

J. D. Schmidt, "An Unusual Emergency House Turbine Installation," *Electric Journal*, Jan. 1929, pp. 26-28; *Mech. Eng.*, Apr. 1929, pp. 302-303.

"60,000 Kw. Turbo Generator for Lakeside," *Elec. World*, Feb. 23, 1929, pp. 381-382.

C. E. Steinbeck, "High Economy Shown by 37,500-Kw. Nine Stage Turbine," *Elec. World*, Apr. 20, 1929, pp. 771-773.

"Large or Special Turbo Generators Recently Placed in Operation," *Elec. World*, Nov. 16, 1929, p. 984.

H. J. Hanzlik, "Design Features of Brooklyn Edison's 110,000 Kw. Turbine," *Power*, Jan. 15, 1929, pp. 82-85.

"160,000 Kw. Unit Goes Into Service at the Hell Gate Station," *Power*, Feb. 5, 1929, pp. 235-238.

"Exhaust From Two 1300 lb. Turbines Will Operate Lakeside's New 60,000 Kw. Unit," *Power*, Mar. 19, 1929, pp. 476-478.

"35,000-Kw. Turbine Generator Moved and Reset in 25 Days," *Power*, June 4, 1929, pp. 918-919.

R. G. Standerwick, "Turbine-Generator Sets for Automatic Steam Substance," *Power*, Dec. 17, 1929, pp. 964-965.

D. Laugharne-Thornton, "Stresses in Foundation Beams due to Dynamical Causes," *World Power*, Aug. 1929, pp. 128-132.

"Power-Plant—'Metrovick' Contracts for Large Units and Small Self-Contained Sets," *World Power*, Oct. 1929, pp. 355-356.

J. P. Den Hartog, "The Mechanics of Plate Rotors for Turbo Generators," *Applied Mechanics* (*A. S. M. E. Trans.*), Vol. 51, No. 10, Jan-April 1929, pp. 1-9.

J. R. Taylor, "Construction of New Generator for Crawford," *Power Plant Engineering*, Jan. 15, 1929, pp. 151-153.

"Dismantling Moving and Resetting a 35,000 Kw. Unit in 25 Days," *Power Plant Engineering*, July 1 and 15, 1929, pp. 730-736; 790-794.

W. Roth, J. D. Schmidt, and J. Wilson, "A Symposium on Couplings for Turbine Units," *Power Plant Engineering*, Aug. 1, 1929, pp. 836-838.

"Ford to Install 110,000 Kw., 1200-lb. Turbine-Generator," *Power Plant Engineering*, Nov. 15, 1929, p. 1219.

"Large Units Continue to Mark Generator Progress," *Power Plant Engineering*, Dec. 15, 1929, pp. 1364-1366.

T. C. Rathbone, "Turbine Vibration and Balancing," *Am. Soc. Mech. Engrs.*, Advance paper for mtg. Oct. 21-23, 1929, 14 pages.

"Turbo-Generator Operation and Maintenance," *Elec. West*, May 15, 1929, pp. 448-455.

"Turbo-Generator Equipment," *Elec. West*, May 15, 1929, pp. 455-457.

"1000 Kw. Steam Turbine in Industrial Service," *Elec. News*, Jan. 1, 1930, p. 51.

H. M. Hobart, "The Modern Steam-Turbine Alternator," *Sibley Jl. Eng.*, June 1929, pp. 228-230, 270-274.

J. Breakey, "Trouble Checking Points for Turbo-Generator Sets," *Power House* (Toronto), Oct. 20, 1929, pp. 25-26.

J. A. Kuyser, "Recent Developments in Turbo-Generators," *Inst. Elec. Engrs.-Jl.*, (Lond.), Sept. 1929, pp. 1081-1117; Oct. 1929, pp. 1262-63.

D. Laugharne-Thornton, "Stresses in Foundation Beams Due to Dynamical Causes," *World Power* (London), Sept. 1929, pp. 234-236.

R. Livingstone, "Large Turbo-Alternator Sets," *Electrician* (London), Jan. 3, 1930, pp. 4-6.

W. Sharp, "Turbo-Generators and Modern Power," *Electrician* (London), Jan. 3, 1930, pp. 10-11.

W. Sharp, "Design and Construction of Large Turbo-Generators," *Electrician* (London), June 7, 1929, pp. 690-692.

"160,000 Kw. Steam Turbo-Generator for the Hell Gate

Power Station, New York," *Engineering* (London), Jan. 4 and 18, 1929, pp. 1-8 and 65-69; Feb. 1, 1929, pp. 128-131.

"Impulse-Turbine Marine Generating Set," *Engineering* (London), Nov. 1, 1929, p. 571.

"Record Efficiency of a Turbo-Alternator," *Engineer* (Lond.), Jan. 25, 1929, pp. 96-97.

"A Large Turbine-Driven Direct-Current Generator," *Engineer* (Lond.), Mar. 29, 1929, pp. 363-364.

300-Kw. Self Contained Geared Turbo-Generator Set," *Engineer* (Lond.), May 31, 1929, pp. 605-607.

J. Eccles, "Acceptance Tests on Turbo-Generators," *Elec. Times* (Lond.), Aug. 29, 1929, pp. 297-298.

"A Very Low Pressure Turbo-Generator," *Elec. Rev.* (Lond.), Jan. 11, 1929, pp. 58-59.

J. A. Kuyser, "Metallurgical Problems of Large Turbo-Generator Design," *Iron and Coal Trades Rev.* (Lond.), Mar. 22, 1929, pp. 463-464.

"Interesting Generating Sets for Imperial Chemical Industries," *Elec. Times* (Lond.), July 4, 1929, p. 27.

G. W. Stubbings, "Instability of Turbo-Alternator Exciters," *Elec. Times* (Lond.), Dec. 13, 1928, pp. 829-830.

"An American Geared Turbo-Generator," *Mar. Engr. & Motorship Bldr.* (Lond.), Mar. 1929, pp. 100-101 and 109.

R. Pohl, "Investigations Regarding Shaft Voltages and Bearing Currents, Especially of Two-Pole Turbo-Generators," *E. T. Z.*, Mar. 21, 1929, pp. 417-422.

R. Pohl, "Turbo-Generator Construction in England," *E. T. Z.*, Sept. 5, 1929, pp. 1297-1300.

W. G. Noack, "Limits of Economy Pressure, Temperature, and Power in Turbo-Generator Design," *E. u. M.*, July 28, 1929, pp. 633-641.

R. Pohl, "New Switch for Quick Deexcitation of Turbo-Generators," *Elektrizitäts-wirtschaft* (Berlin), Jan. 1, 1929, pp. 1-6.

O. E. Rosa, "Economy in Parallel Operation of Steam Turbines," *Brennstoff u. Waermewirtschaft* (Berlin), June 1929, pp. 203-206.

A. Bross, "Testing Equipment for Steam Turbines in Testing Station of Muelheim Works of Siemens and Schuckert," *Siemens-Zeit.* (Berlin), Dec. 1929, pp. 872-873.

A. Gorfinkel, "Actual Tendencies in the Performance of Turbo-Alternator Sets," *Génie Civil* (Paris), Mar. 9 and 16, 1929, pp. 237-243 and 261-263.

"The Turbo-Alternator of 75,000 Hp. of the Future Electric Plant of Saint-Denis, *Génie Civil* (Paris), July 27, 1929, p. 93.

G. Savourey, "Turbo-Generator for Testing Out the Claude-Boucherot Process," *Industrie Electrique* (Paris), Mar. 25, 1929, pp. 136-139.

M. Marchoix, "Air Pump vs. Ejector," *Science et Industrie* (Paris), Mar. 1929, pp. 149-152.

Savourey and Collignon, "Turbo-Alternator Set of 1000/1200 Kw. of Union Electrique de L'Ouest at Caen," *Revue de Electricité et de Mechanique* (Paris), July and Aug. 1929, pp. 6-10.

R. Soderberg, "Mechanical Problems in Design of Big Turbo-Generators," *Teknisk Tidskrift* (Stockholm), July 6 and Sept. 7, 1929, pp. 119-124, 151-158.

J. A. Kuyser, "Turbo-Generators," *Indus. Australian Min. and Std.* (Melbourne), May 9, 1929, p. 340.

"The Metropolitan Vickers Self-Contained Turbo-Generator," *Far East Rev.* (Shanghai), Jan. 1929, p. 12-15.

"A 20,000-Kw. Turbo-Alternator for the Japanese Imperial Government Railways, *Far East Rev.* (Shanghai), June 1929, pp. 271.

N. A. Davidov, "Tests of a Rateau 17,500 Kw. Turbo-Generator for Government Electric Power Plant (Moges), *Izvestiya Teplotechnicheskovo Instituta* (Moscow), No. 9, 1929, pp. 5-49.

E. I. Doty, "The Assembly of Shafts and Rotors," *Electric Journal*, May 1929, pp. 206-209.

M. W. Smith, "Developments in the Umbrella-Type Waterwheel Generators," *Electric Journal*, June 1929, pp. 253-254.

M. W. Smith, "Large Flywheel Effect, High Efficiency, Low Exciter, Capacity, Are Obtained Through Standardization in Design," *Electric Journal*, Oct. 1929, pp. 471-474.

E. L. Doty, "Assembly Work Improved by Electric Heaters," *Elec. World*, Feb. 23, 1929, pp. 384.

D. E. Brainard, "Glimpses of a Design Engineer's Work," *Sibley Jl. of Eng.*, May 1929, pp. 189-192, 213-214.

J. R. Dunbar and H. A. Ricker, "The 28,500-Kv-a. Generators for Paugan Falls," *Eng. Jl.* (Montreal), Mar. 1929, pp. 129-134.

J. R. Dunbar and H. A. Ricker, "28,500-Kv-a. Generators for Paugan Falls," *Eng. Jl.* (Montreal), June 1929, pp. 385-388.

K. Bobek, "Generators for Hydroelectric Plants," *Siemens-Zeit.*, Mar. 1929, pp. 177-184; Apr. 1929, pp. 232-240.

"Large Vertical Alternators for Perak River Hydro-Electric Power Company," *Far East Rev.* (China), Nov. 1929, pp. 508-509.

R. H. Park, *Two-Reaction Theory of Synchronous Machines*, A. I. E. E., TRANS. Vol. 48, July, 1929, p. 716.

W. H. Feldmann, "Modern Synchronous Motors," *Elec. World*, Oct. 5, 1929, pp. 675-679.

E. C. Souder, "Torque and Power Factor Determine Synchronous Motor Selections," *Elec. World*, Dec. 14, 1929, pp. 1182-87.

S. P. Bordeau, "Synchronous Motor Starting Reduced to Pushing a Button," *Power*, June 4, 1929, pp. 920-923.

F. Jeffrey, "Synchronous Motors Increase in Size and Applications," *Power*, July 2, 1929, pp. 8-9.

R. H. Rogers, "What Synchronous Motors Offer to Industry," *Indus. Eng.*, Nov. 1929, pp. 575-577.

H. M. Sayers, "Synchronous Motors," *Elec. Rev.* (Lond.), Sept. 6, 1929, p. 391.

A. Heyland, "Starting Synchronous Motors with Flush Inductors or Salient Poles, by Means of a Transverse Field Relative to Poles," *R. G. E.*, May 18, 1929, pp. 769-774.

E. A. Ter-Markarjanz, "Theoretical and Experimental Investigation of the Synchronous Reaction Motor," *Archiv. fur Elektrot.* (Berlin), Apr. 8, 1929, pp. 612-644.

V. A. Fynn, "Synchronous Motors with Variable Position of Field Axis Relatively to the Rotor," *E. u. M.*, Jan. 13 and 20, 1929, pp. 25-34 and 49-58.

C. Schenfer, "Synchronous Motor with Automatic Regulation of Power Factor," *E. u. M.*, Mar. 17, 1929, pp. 217-219.

G. M. Chute, "Synchronous Motors for General Use," *Ingenieria Internacional*, Sept. 1929, pp. 454-456.

T. Kumazawa, "On the Distortions of A. C. Wave-Forms Affected by Huntings," *Inst. Elec. Engrs. of Japan-Jl.*, Jan.-Feb. 1929, pp. 5-7.

C. D. Kester, "Synchronous Motors in Industry," *Ingenierai Internacional*, Nov. 1929, p. 557.

D-C. MACHINES

The use of fabricated construction which has rapidly increased during the past few years has been more extensively applied to direct current machines of various sizes. The use of rolled-steel field yokes is practically universal in large sized machines.

Greater attention is being given by operating companies to ventilation of machines so as to prevent recirculation of air causing high ambient temperatures. The use of the volute housing in which the ventilation of the machine is used to force the heated air, through ducts, out of the building has been extended and the synchronous converters which the General Electric Company is constructing for the New York City Board of Transportation will be equipped with this type of ventilation.

Synchronous Converters. The largest 60-cycle converters for railway service, and the first to use 12 phase for this application, are under construction by the General Electric Company for the Board of Transportation of the City of New York. They will have a nominal rating of 4000 kw. at 625 volts with a 200 per cent rating for five minutes and 300 per cent rating for one minute. A 25-cycle converter for chemical work

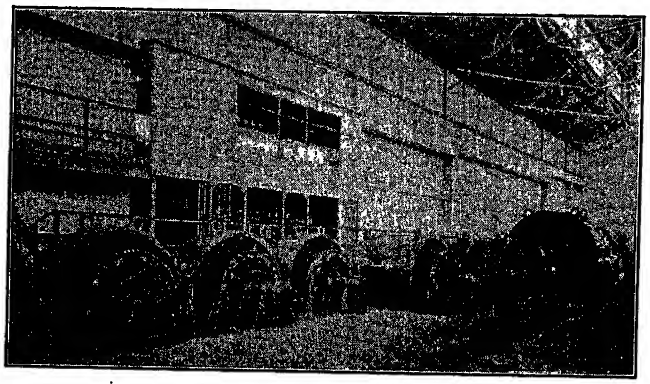


FIG. 19—D-C. MOTORS DRIVING THE 12-IN. HOT-STRIP MILL

The six 1250-hp. motors driving finishing stands are mounted on common bedplate. 4500-hp., 150/450 rev. per min. roughing mill motor in background. The Sharon Steel Hoop Co., Sharon, Pa.

having a current rating of 16,000 amperes for voltages from 270 to 340 is being built. It is believed that this is the largest current rating of a synchronous converter for the extremely high load factor commonly experienced in electrolytic work, although a similar machine was built several years ago for 17,000 amperes lighting service.

An extremely interesting development is a 3000-kv-a. 60-cycle 300-volt converter being built by the General Electric Company for hydrogen cooling. This machine is to be used in a chemical plant in which the complete enclosure with hydrogen cooling serves as a protection against fumes as well as secures the greater effectiveness of cooling. No operating information has been secured at this writing.

An example of the extensive use of fabricated construction is found in some 3900-kw. booster-type 60-cycle converters being built for the Commonwealth Edison Company of Chicago by the Westinghouse Company. With the exception of the pedestals, the entire machine is made of structural steel. The rolled frame and welded type of construction in the manufacture of the bedplate, commutator, spider and brush rigging can be seen in Fig. 18. The same fabricated type of construction is being used on two 5440-kw. 25-cycle field controlled converters built by the same manufacturer for the Roessler and Hasslacher Chemical Company of Niagara Falls.

Generators and Motors. The Westinghouse is now building a 10,000-hp. blooming-mill-drive involving a number of interesting features. The upper and lower rolls are each independently driven by a 5000-hp. motor, the pinion and pinion housing normally used to connect the upper and lower rolls being completely eliminated. The two motors are located at the same end of the mill giving improved efficiency, greater flexibility, and reduced first cost to the steel mill. The power for the drive is obtained from an induction motor-generator set having three d-c. generators operating in parallel.

The General Electric Company has built an equipment for a 12-in. hot-strip mill consisting of six 1250-hp. motors on a single base arranged on 8 ft. centers. Due to the wide range in basic speeds, from 103 to 312 rev. per min., double motors were used for three of the units.

An interesting motor-generator set has been built by the General Electric Company for the drive of a 7000-hp. and 1650-hp. reversing motor. The motor-generator set is built with three 2400-kw. generators designed to operate in parallel. Both the generators and the motors are equipped with special field windings and excitation control designed to give characteristics for a proper division of load as the five machines are connected to one bus.

Exciters. During 1929 there has been a definite trend toward providing large a-c. machines with individual exciters and a greater use of sub-exciters, that is, small exciters to provide separate excitation for the main exciters. Several large exciters for recent large turbo generators were provided with sub-exciters for mounting on the main turbine shaft. The advantages of the sub-exciter are lower losses, greater stability, and quick response.

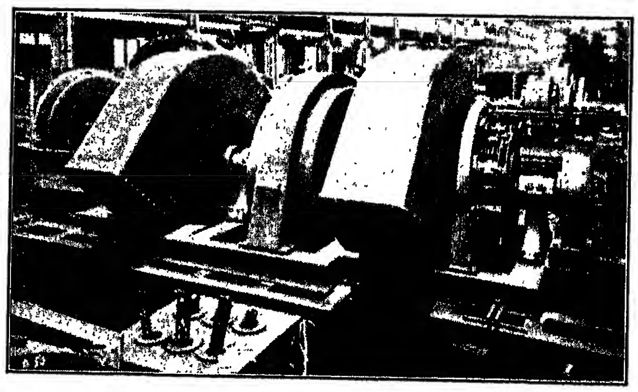


FIG. 20—A GENERAL ELECTRIC 1500-KW. SYNCHRONOUS MOTOR, D-C. GENERATOR SET WITH VOLUTE VENTILATING HOUSING

Where it is necessary to obtain low excitation voltage from exciters feeding a-c. generators which may be required to supply charging current to long transmission lines, differential shunt fields have been employed on the exciters. These fields are about 10 per cent as heavy as the main shunt fields and are separately excited which permits the exciter to operate below its normal residual voltage value. This is especially necessary where voltage regulators are used, as the operation of the regulator depends upon its swinging the voltage beyond

the average value which applies to the collector rings of the a-c. generators. By the use of the differential shunt fields the main rheostat can be entirely eliminated even when the excitation required is below that of the residual of the exciter.

For some machines, usually synchronous condensers, it is necessary to provide excitation voltage down to zero volts. The General Electric Company obtains this condition by providing a Wheatstone Bridge arrangement in the rheostat of the separately excited main field. With this arrangement, voltages down to zero and even in a reverse direction can be obtained without resorting to special field windings on the main exciter.

Ordinary a-c. generators when used with quick response excitation require an exciter voltage change of the order of 400 to 600 volts per second. This lower value of voltage change can be obtained with exciters without the use of laminated yokes.

In a quick response excitation system where voltage required from the exciter is greater than 750 to 1000 volts per second, eddy-currents in solid frames and in thick laminations in pole pieces materially retard the rate of change of voltage. To overcome this difficulty the Westinghouse Company has designed the exciter yoke of laminations held together by insulated end plates and the pole pieces are made of thin laminations held together by insulated rivets. This construction will permit speeds of response of from 3000 to 4000 volts per second. On one synchronous condenser installation made by the General Electric Company a maximum rate of rise on the main exciter was in excess of 7000 volts per second. These extremely high speeds are used at present on synchronous condensers only and then in only rare cases.

BIBLIOGRAPHY

Direct-Current Machines

M. E. Wagner, "Making D-C. Generators Build Up Voltage," *Power*, Aug. 13, 1929, pp. 253-255.

M. E. Wagner, "Why D-C. Generators Reverse Polarity," *Power*, Sept. 24, 1929, pp. 489-491.

C. Lynn, "Operation of Three-Wire Generators," *Power*, Jan. 28, 1929, pp. 135-137.

H. D. James, "Adjusting Motor Speeds," *Indus. Eng.*, July 1929, pp. 366-368.

C. A. Johnson, "Adapting Auto-Starters to Changed Conditions," *Indus. Eng.*, Nov. 1929, pp. 580-582.

H. E. Stafford, "Points Worth Knowing for Maintenance of Direct Current Generators and Motors," *Power House* (Toronto), Apr. 5, 1929, pp. 36-39 and 53.

C. V. Hill, "Variable Speed A. C. Commutator Motors," *Elec. Rev.* (Lond.), May 3 and 10, 1929, pp. 783-784.

W. E. Warner, "Direct Current Electric Motors," *Ice and Cold Storage* (Lond.), Oct. 1929, pp. 254-255.

E. Rosenberg, "Development in Design of Regulating Pole-Crossfield Machines," *E. T. Z.*, Aug. 15, 1929, pp. 1188-1190.

H. Sequenz, "Fluctuations in Voltage as Results of Commutation in Direct-Current Generators, *E. T. Z.*, Aug. 22, 1929, pp. 1221-25; Dec. 5-12, 1929, pp. 1775-78, 1807-1810.

H. Voight, "Liability in the Operation of D. C. Shunt Motors," *E. u. M.*, Mar. 3, 1929, pp. 176-178.

L. Boernstein, "New Three-Phase Commutator Motor Type DNP," *AEG Progress* (Berlin), Oct.-Nov. 1929, p. 331.

C. Okawa, "Theory of Ripples in D. C. Machines," *Inst. Elec. Engrs. of Japan-Jl.*, Aug. 1929, pp. 852-869.

S. Nagao, "Dynamic and Regenerative Brakings in D-C. Railway Motors," *Ohm* (Tokyo), Nov. 1929, pp. 527-528.

E. S. Bundy, *A 40,000-Kw. Variable Ratio Frequency Converter Installation*, A. I. E. E. Trans., Vol. 49, Jan. 1930, pp. 245-255.

H. Laviers, Jr. and H. S. Littlewood, "Insuring Correct Polarity of Synchronous Converters," *Electric Journal*, Dec. 1929, pp. 564-565.

R. E. Powers, "Safe Operation of Rotary Converters," *Power*, Mar. 19, 1929, pp. 470-472.

H. N. Blackmon, "How to Select Equipment for Changing A-C. to D-C. Power," *Indus. Power*, Nov. 1929, pp. 37-38, 110-112.

F. Johnstone-Taylor, "Converting Apparatus," *Power House* (Toronto), Feb. 5, 1929, pp. 32-33; Mar. 20, 1929, p. 30.

T. S. Andrew, "The Synchronous Forces in a Motor Converter," *Elec. Rev.* (London), Aug. 9, 1929, pp. 223-225.

"Automatic Rotary Converters," *Elec. Times* (Lond.), Dec. 12, 1929, pp. 1027-29.

L. Dreyfus, "Theory of Synchronous Converter with Special Consideration of Compensating Processes from Short Circuits on Direct Current Side," *Archiv. fur Elektrot.*, Feb. 14, 1929, pp. 497-525.

L. Dreyfus, "Design and Calculation of Damping Arrangement of the Synchronous Rotary Converter," *Archiv. fur Elektrot.*, Nov. 19, 1929, pp. 181-216.

R. Meller, "New Connection for Rotary Converter with Commutator Poles with Special Regard to Equipment for Converting Single-Phase Current into Direct Current Voltage Capable of Regulating," *E. u. M.*, Dec. 1, 1929, pp. 1045-48.

L. Finkelstein, "Flywheel Type Converters for S. W. Africa," *AEG Progress* (Berlin), Feb. 1929, pp. 43-48.

R. Pettinger, "Measures for Constant Operation of Rotary Convertors in Parallel Performance with Storage Batteries at Voltage and Frequency Fluctuations," *Siemens Zeit.*, May-June 1929, pp. 346-354.

E. Kloss, "Behavior of Converters in Case of Trouble in Networks and Prevention of Interruption of Service," *Siemens Zeit.*, Oct. 1929, pp. 617-626; Dec. 1929, pp. 859-872.

F. Hillebrand and G. Meiners, "Automatic Reswitching of Rotary Converters and Synchronous Machinery in Case of Short-Time Troubles in Three-Phase Network Systems," *Elektrizitätswirtschaft* (Berlin), Aug. 2, 1929, pp. 437-440.

M. Mueller and F. Emmerich, "Large Rotary Converter for the New York Edison Company," *Brown Boveri Review*, Nov. 1929, pp. 295-302.

P. Toulon, "Powerful Electric Converter, Spark Controlled," *Rev. Gén. Elec.* Mar. 30, 1929, pp. 477-482; Apr. 6, 1929, pp. 518-526.

H. Bergfeldt, "Converters for Arc Lamps of Cinematographic Apparatus and Projectors," *Energia Elettrica* (Madrid), Mar. 25, 1929, pp. 65-66.

"Automatic Convertor at Ueno Station of the Tokyo Underground Railway," *Far East Rev.* (Shanghai), May 1929, pp. 209-212 and 224.

A. Matano, "A Study on a Rotary Converter," *Inst. Elec. Engrs. of Japan-Jl.*, May 1929, pp. 578-610.

F. T. Hague and G. W. Penney, *Influence of Temperature on Large Commutator Operation*, A. I. E. E. Jl., Vol. 48, June 1929, pp. 473-476.

"A Spiderless Commutator," *Electric Journal*, Feb. 1929, pp. 72.

G. M. Little, "Properties and Tests of Carbon Brushes for Motors and Generators," *Electric Journal*, May 1929, pp. 194-198.

W. C. Kalb, "Some of the Variations in Carbon Brush Specifications," *Power*, June 25, 1929, pp. 1049-51.

W. C. Kalb, "What the Power Engineer Can do for Brush Standards," *Power*, July 9, 1929, pp. 46-47.

M. Phillips, "Searching Out Causes of Commutator Sparking," *Power*, Dec. 17, 1929, pp. 966-967.

"Safer Commutator Stoning," *Elec. World*, Oct. 12, 1929, p. 740.

G. M. Little, "Properties and Tests of Carbon Brushes for Motors and Generators," *Power Plant Engineering*, Aug. 1, 1929, pp. 839-841.

J. Albrecht, "Elements of Commutation," *Iron & Steel Engineer*, Feb. 1929, pp. 82-91.

"Symposium Carbon Brushes," *Iron & Steel Engineer*, Mar. 1929, pp. 101-116.

R. H. Newton, "The Selection and Application of Direct Current Brushes," *Iron & Steel Engineer*, Mar. 1929, pp. 127-130.

J. V. Dobson, "Maintaining Carbon Brushes for Good Commutation," *Elec. Ry. Jl.*, Nov. 1929, pp. 1061-63.

"Commutator Testing Device," *Ry. Elec. Engr.*, Apr. 1929, pp. 128-129.

"Commutator Mica Cutting Machine," *Engineering* (Lond.), Nov. 22, 1929, p.

B. G. Churcher, "The Measurement of the Alternating Components in the Electromotive Force of Commutating Machinery," *M-V Gazette* (Manchester), Jan. 1929, pp. 183-184.

J. Neukirchen, "Commutator Brush as a Loose Contact," *E. T. Z.*, Jan. 10 and 17, 1929, pp. 55-58 and 82-84.

H. Bechmann, "Influence of Circumferential Velocity of Commutators on Load Capacity," *E. T. Z.*, Jan. 24, 1929, pp. 123-124.

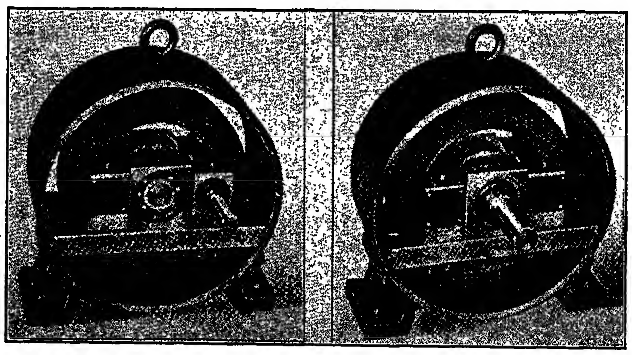
J. M. Pestarini, "Problem of Commutation," *Rev. Gén. Elec.*, June 22, 1929, pp. 965-973.

J. M. Pestarini, "Problem of Commutation," *Rev. Gén. Elec.*, June 29, 1929, pp. 1003-07.

M. Perrier, "Brush Traces on the Rings of Synchronous Machinery," *Rev. Gén. Elec.*, June 29, 1929, pp. 1009-13.

Induction Motors

One of the most significant developments of the year is the undertaking by the various manufacturers of this country, to produce a line of motors which will comply with the standardized mounting dimensions approved by the National Electric Manufacturers' Association. Some manufacturers are redesigning the motors electrically while dimensions are being changed. These new lines should appear on the market during the year 1930.



A A

Fig. 21—The Crocker Wheeler Speed Changer (Two Views)

a. "C" type reducer viewed from high-speed side with covers removed
b. "C" type reducer view from low-speed side with covers removed

During the past year the developments of small induction motors has seen a more extensive application of totally enclosed motors, many of them being in the explosion-proof classification. The enclosed fan-cooled principle has been extended to larger motors; for example, the Louis Allis Company report the development of an explosion-proof self-ventilated motor which can be furnished in sizes up to 75 hp. and designed to withstand internal pressures up to 100 lb. per sq. in. The use of the enclosed fan-cooled motor is finding some application as a drive for fuel pulverizer mills. As an adjunct to the smaller line of induction motors the Crocker Wheeler Company has developed a new line of toothless speed changers which are reported to have an efficiency of 99 per cent at three-quarters load and 98½ per cent at full load.

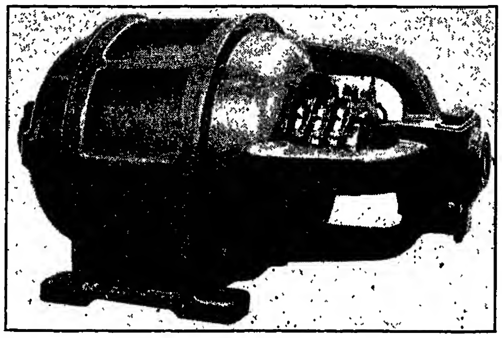


Fig. 22—Five Kw., 60/180-Cycle Single Unit Frequency Changer Eight Per Cent Regulation

The use of the capacitor motor has been extended, for some applications with the capacitor in service continuously and for others only during the starting operation. The General Electric Company has brought out single-phase capacitor motors for use in driving propeller type fans. By the use of a high resistance rotor the speed of the fan may be controlled by varying the applied voltage, as by means of taps on an autotransformer. The Electrical Machinery Company has put on the market a scheme of connecting a capacitor across the induction motor terminals during starting in order to reduce the kv-a. in-rush. After the motor is up to speed, the capacitor is disconnected from the line and is available for use in starting other motors.

For furnishing power to high speed hand tools a new type of single-unit frequency changer has been developed by the General Electric Company which is adaptable for a change of frequency from 60 to 180 cycles. It combines in a single unit the function of a frequency changer and a driving motor of the conventional two unit set. By eliminating the base, coupling, and driving motor the single unit frequency changer occupies a minimum of room.

The use of atwo circuit induction motor in which only one circuit is used for starting has been developed to reduce the current in-rush during starting.

The General Electric Company has built a 27,500-hp. induction motor which is part of a 20,000-kw. induction-synchronous frequency-changer set now in operation on the system of the Buffalo General Electric Company. Two similar sets are being built for the Union Electric Light and Power Company of St. Louis. The Canadian

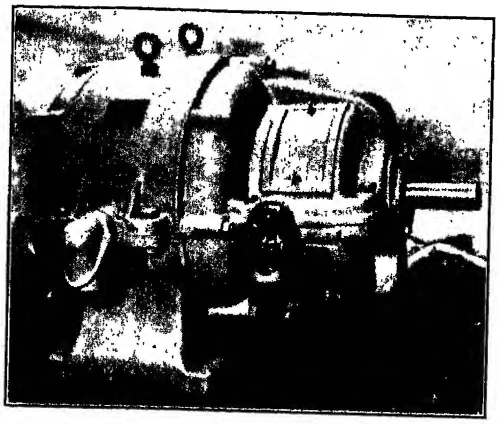


FIG. 23—INDUCTION MOTOR FURNISHED THE WELLAND SHIP CANAL BY THE CANADIAN WESTINGHOUSE CO.

The top half of the frame may be removed to replace parts

Westinghouse Company is furnishing some 200-hp. motors for the Welland Ship Canal of rather special construction illustrated in Fig. 23. The object of the design is to make it possible to lift the top half of the frame and then remove the complete electrical and mechanical parts of the lower half so that spare parts could be quickly inserted in the frame.

Progress has been made in the application of polyphase adjustable speed a-c. motors for the needs of the textile industry; as an example, one manufac-

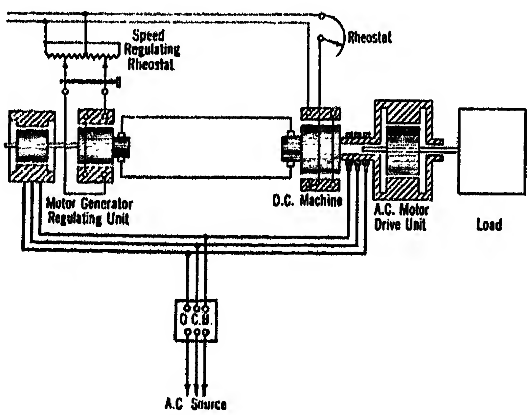


FIG. 24—DIAGRAM OF CONNECTIONS

turer has received an order for 2000 such commutator type motors having shunt characteristics and rated 3-hp. at 1650 rev. per min. maximum speed. The motors are to be used for driving full-fashioned hosiery knitting mills requiring close speed regulation and adjustable speed which is readily obtained by shifting the brush position.

A new scheme of speed control has been developed by Sargent and Lundy of Chicago, making use of an induction motor whose stator is connected rigidly to the armature of a d-c. motor and mounted on bearings so that it can be rotated. The d-c. motor may drive or be driven by a d-c. generator whose voltage is adjustable from maximum positive through zero to maximum negative so that the so-called stator may be rotated in either direction at any speed within its maximum limits. Those now in operation have been built to have a speed range of from 100 per cent to 40 per cent. The d-c. motor and generator may be only a small percentage of the total horsepower of the main motor as they supply only the difference in power required between the operating speed and synchronous speed. The capacity of the direct current machines now in operation is approximately 16 per cent of the induction motor rating.

BIBLIOGRAPHY

ASYNCHRONOUS MACHINES

T. Spooner and C. W. Kincaid, *No-Load Induction Motor Core Losses*, A. I. E. E. TRANS., Vol. 48, Jan. 1929, pp. 645-654.

H. C. Specht, *The Fundamental Theory of the Capacitor Motor*, A. I. E. E. TRANS., Vol. 48, April 1929, pp. 607-613.

W. J. Morrill, *The Revolving Field Theory of the Capacitor Motor*, A. I. E. E. TRANS., Vol. 48, April 1929, pp. 614-629.

C. J. Koch, *Line-Start Induction Motors*, A. I. E. E. TRANS., Vol. 48, April 1929, pp. 633-641.

L. A. Doggett and E. R. Queer, *Induction Motor Operation with Non-Sinusoidal Impressed Voltages*, A. I. E. E. TRANS., Vol. 48, Oct. 1929, pp. 1217-1220.

W. J. Branson, *Polyphase Induction Motors—A Labor Saving Method of Calculating Performance from Previously Determined Constants*, A. I. E. E. TRANS., Vol. 48, Jan. 1930, pp. 319-328.

B. F. Bailey, *The Condenser Motor*, A. I. E. E., Apr. 1929, pp. 273-276.

L. J. Cissna, "Controlling Twelve Motors with Two Control Equipments," *Electric Journal*, Sept. 1929, pp. 393-397.

"Induction Motors," *Elec. World*, Feb. 9, 1929, pp. 294-295.

"Performance of Capacitor Motors Established by Test," *Elec. World*, Mar. 16, 1929, p. 532.

G. R. Anderson, "Characteristics of Line-Start Motors," *Elec. World*, May 4, 1929, pp. 873-875.

J. R. Hopkins, "Line-Start Motors Require Wider Pulleys and Belts," *Elec. World*, Aug. 3, 1929, pp. 222-223.

H. L. Smith, "Motor Starting Current Reduced by Special Wiring," *Elec. World*, Sept. 7, 1929, pp. 474.

M. E. Wagner, "Causes of and Remedies for Faulty Induction Motor Operation, *Power*, Sept. 3, 1929, pp. 370-373.

M. E. Wagner, "Locating Winding Faults in Alternating Current Motors," *Power*, Oct. 29, 1929, pp. 680-683.

C. W. Drake, "Why it is Advisable to Check up on Motor Loads," *Indus. Eng.*, June 1929, pp. 318-319.

J. R. Hopkins, "Linestart Motors Require Wider Pulleys and Wider Belts," *Indus. Eng.*, July 1929, pp. 372-373.

H. D. James, "Series Parallel and Other Methods of Controlling Motor Speed," *Indus. Eng.*, Nov. 1929, pp. 568-570.

R. H. Rogers, "What Multi-Speed Motors Offer to Industry," *Indus. Eng.*, Dec. 1929, pp. 611-613.

C. G. Green, "The Elementary Principles of Induction Motor Operation," *Nat. Eng.*, Aug. 1929, pp. 363-367.

W. E. Warner, "Notes on Induction Motors," *Power House*, Nov. 5, 1929, pp. 26 and 32.

C. H. S. Tupholme, "Squirrel-Cage Induction Motors," *Mech. World*, Aug. 9, 1929, pp. 119-120.

E. W. Henderson, "Do Linestart Motors Necessitate Changes in Design?," *Machine Design*, Dec. 1929, pp. 38-41.

J. R. Hopkins, "Linestart Motors Require Wider Pulleys and Wider Belts," *Cement, Mill and Quarry Paper Industry*, July 1929, pp. 54-55; June 1929, pp. 483 and 485.

G. F. Heath, "A Speed Variation Scheme," *Elec. Rev.* (Lond.), Jan. 25, 1929, pp. 145-146.

G. Windred, "Notes on Single-Phase Motors," *Elec. Rev.* (Lond.), Sept. 27, 1929, pp. 516-518.

L. H. A. Carr, "The Circle Diagram of the Induction Motor," *Electrician* (Lond.), July 5, 1929, p. 24.

J. Hope, "Controlling Induction Motors." *Mech. World*, Nov. 15, 1929, pp. 468-469.

C. H. S. Tupholme, "The Polyphase Squirrel-Cage Motor in Industry," *Mech. World*, Sept. 20, 1929, pp. 263-264.

C. W. Olliver, "The Starting of Squirrel-Cage Motors," *Colliery Eng.* (Lond.), Feb. 1929, pp. 65-68.

F. J. Taylor, "Variable Speed A. C. Motors," *Colliery Guardian* (Lond.), Sept. 6, 1929, pp. 893-896; Sept. 13, 1929, pp. 1003-1005.

M. Kloss, "Starting Tests with Three-Phase Squirrel Cage Motor with Centrifugal Pulleys," *E. T. Z.*, Feb. 14, 1929, pp. 223-225.

W. Spaeth, "Electromechanical Generator of Oscillations—Swinging Motor," *E. T. Z.*, Mar. 28, 1929, pp. 455-458.

F. Dittrich, "Influence of Unequal Voltages on the Power Consumption of Three-Phase A-C. Installations," *E. T. Z.*, June 27, 1929, pp. 931-933.

J. Thieme, "Geometry of Compensated Induction Motors, *E. T. Z.*, Aug. 8, 1929, pp. 1151-1153.

M. Liwschitz, "Regulation Units," *Archiv. fur Elektrot.*, Sept. 28, 1929, pp. 577-582.

M. Liwschitz, "Regulation of Electric Circuits with Variable Frequency," *Archiv. fur Elektrot.*, Sept. 28, 1929, pp. 583-587.

H. E. Linckh, "Determination of Additional Losses in Three-Phase Induction Motors," *Archiv. fur Elektrot.*, Nov. 5, 1929, pp. 19-39.

K. Dreyfus, "New Principle in Regulation for Cascade Connections of Three-Phase Induction Motors in Three-Phase Commutator Machines," *Archiv. fur Elektrot.*, Nov. 5, 1929, pp. 66-76.

A. Thomaelen, "Theory of Three-Phase Motors with Double Squirrel-Cage Rotor," *Archiv. fur Elektrot.*, Dec. 7, 1929, pp. 205-208.

A. Brueser, "Theory of Three-Phase Double Squirrel-Cage Motor with any Number of Conductors of Windings," *Archiv. fur Elektrot.*, Dec. 7, 1928, pp. 289-311.

E. Kuebler, "Combined Magnetic Field of Asynchronous Three-Phase Motors at Short Circuit and in Operation," *Archiv. fur Elektrot.*, Dec. 17, 1929, pp. 407-432.

H. Lund, "Double-Squirrel-Cage Motor as a Substitute for the Slip-Ring Motor," *E. u. M.*, May 5, 1929, pp. 373-377.

N. Landesberg, "Phase Compensation and Compounding of Three Phase Induction Motors," *E. u. M.*, May 12, 1929, pp. 393-395.

A. Velisek, "New Code Conditions for Connecting Squirrel Cage Motors of Vienna Municipal Electricity Works," *E. u. M.*, Aug. 25, 1929, pp. 713-716.

F. Pichler, "Experience with Squirrel-Cage Motors in the Network of the Franz Pichler Electricity Works, at Weiz," *E. u. M.*, Sept. 8, 1929, pp. 777-778.

W. T. Kassjanoff, "Hysteresis Starting of Induction Motors," *E. u. M.*, Oct. 6 and 13, 1929, pp. 865-873; pp. 890-893.

E. Gruenwald, "From the Multiple-Phase to the Single-Phase Asynchronous Machine," *E. u. M.*, Nov. 17, 1929, pp. 1001-08; Jan. 26, 1930, pp. 73-81.

H. Stenger, "Individual Driving of Looms." *V. D. I.*, May 9, 1929, p. 332.

Artweger, "Special Squirrel-Cage Motors for Short-Time Operation, Developed by Richter," *VDE Fachberichte* (Aachen), 1929, pp. 83-86.

M. Kloss, "Starting Tests with Three-Phase Squirrel Cage Motor with Centrifugal Pulleys," *Elektrizitätswirtschaft*, (Berlin), Mar. 1, 1929, pp. 113-118.

Von J. Knust, "Consumption of Three-Phase Motors in Practise," *Elektrizitätswirtschaft* (Berlin), Apr. 2, 1929, pp. 193-201.

E. M. K. Sommer, "Are Three-Phase Induction Motors in a Supply Network to be Disconnected Automatically in Case of Downward Voltage Fluctuations? "*Elektrizitätswirtschaft* (Berlin) July 2, 1929, pp. 388-393.

R. Elsaesser and O. Stock, "Starting Conditions of Slip-Ring Motors," *Elektrizitätswirtschaft* (Berlin), Dec. 1, 1929, pp. 598-661.

W. Stark, "Operation Experience with Asynchronous Reactive Power Machine," *Siemens-Zeit.*, May-June 1929, pp. 339-346.

"Application of Double-Cage Motors, St. Halas," *A E G Progress* (Berlin), Mar. 1929, pp. 53-54.

"Special Types of Induction Motors," *A E G Progress* (Berlin), Oct.-Nov. 1929, pp. 307-311.

"Separately Ventilated Slip-Ring Housing for Slow-Speed Induction Motors for Explosive Places," *A E G Progress* (Berlin), Oct.-Nov. 1929, pp. 312-313.

"A Self-Starting Motor of the Cage-Rotor Type," *Eng. Progress*, Mar. 1929, pp. 71-72.

G. Benishke, "Die Asynchronen Wechselfeldmotoren," *Springer*, 1929, 123 pages.

H. F. Schait, "Kompensierte und Synchronisierte Asynchronmotoren," *Springer*, 1929, 104 pages.

A. Mauduit, "Theory of Induction Motor with Polyphase Rotor," *Rev. Gén. Elec.*, July 6, 1929, pp. 5-15.

J. Froidevaux, "Study of the Distribution of Current Density in the Rotor Bars of Squirrel Cage Motors," *Rev. Gén. Elec.* Aug. 17, 1929, pp. 257-262.

P. Girault, "Momentary Excess Torque for Multi-Phase Induction Motors," *Rev. Gén. Elec.*, Sept. 21, 1929, pp. 449-452.

R. David, "Momentary Excess Torque for Multiphase Induction Motors," *Rev. Gén. Elec.*, Nov. 2, 1929, pp. 720-722.

"Variable Speed Electric Machines," *Houille Blanche* (Lyon), Mar.-Apr. 1929, pp. 40-47; May-June 1929, pp. 76-86; Nov.-Dec. 1929, pp. 169-182; Sept.-Oct. 1929, pp. 147-150.

"Condenser Motor," *Industrie Electrique* (Paris), Sept. 10, 1929, pp. 391-394.

"Double Squirrel-Cage Motors," *Electrician* (Paris), May 15, 1929, pp. 229-233.

L. Beurrier, "Electric Machinery for Variable Speed," *Indus. Mecaniques* (Paris), May 1929, pp. 56-66.

"Electric Machinery for Variable Speed," *Pratique des Industries Mecaniques* (Paris), Sept. and Oct. 1929, pp. 245-254; pp. 290-300.

M. J. Bethenod, "Automatic Throw-In Devices for Squirrel-Cage Motors," *Societé Franc. des Electriciens, Bull.* (Paris), Sept. 1929, pp. 923-926.

T. D. Jemtland, "Squirrel-Cage Motors," *Elektroteknisk Tidskrift* (Oslo), June 25, 1929, pp. 245-251.

L. Dreyfus, "Synchronous Parallel Operation of Polyphase Asynchronous Motors," *Teknisk Tidskrift* (Stockholm), Oct. 5, 1929, pp. 167-174.

C. Vila, "Speed Regulation in Three-Phase Motors," *Electricidad* (Barcelona), July 1929, pp. 7-11.

F. Neri, "Self-Excitation of an Asynchronous Self-Compensating Type of Motor," *Elettrotecnica* (Milan), Aug. 5, 1929, pp. 517-520.

A. C. Darmantshev, "Squirrel-Cage Motors," *Electrichestvo* (Moscow), No. 9 10, May 1929, pp. 222-225.

C. Shenfer, "The Current Curves in Rotor Bars of Asynchronous Motors," *Electritshestvo* (Leningrad), Oct. 1929, pp. 503-504.

J. M. Huber, "Role of the Squirrel-Cage Motor in Power Economy," *Electretchestvo* (Leningrad), Oct. 1929, pp. 512-516.

C. Schenfer, "Simple Formula for Calculation of Slot Leakage of Asynchronous Motors," *Vestnik Teoreticheskoy i Experimentalnoy Elektrotechniki* (Moscow), Dec. 1928, pp. 475-478.

S. Mitomo, "Comparing Heyland's and Steinmetz's Circle Diagram for the Polyphase Induction Motor," *Electrotech. Soc. of Waseda-Jl.* (Tokyo), Jan. 1929, pp. 7-13.

S. Mita, "Characteristics of the Polyphase Induction Motor with Saturation Transformers in Series with the Primary," *Inst. Elec. Engrs. of Japan, Jl.*, Feb. 1929, pp. 225-237.

T. Sugie, "On the System of Asynchronous Generator," *Electrotech. Soc. of Waseda* (Tokyo), Aug. 1929, pp. 285-300.

T. Ueda, "Motors Suitable for Both 50 and 60 Cycles," *Ohm* (Tokyo), Nov. 1929, pp. 523-524.

Mercury Arc Rectifiers

Since January 1, 1929, a total of 78 mercury arc rectifiers sets with an aggregate rating of 179,900 kw. have been put in operation or on order in the United States and Canada. The largest part of this equipment is for railway service, but some will be used for other applications; for example, four large units each having a

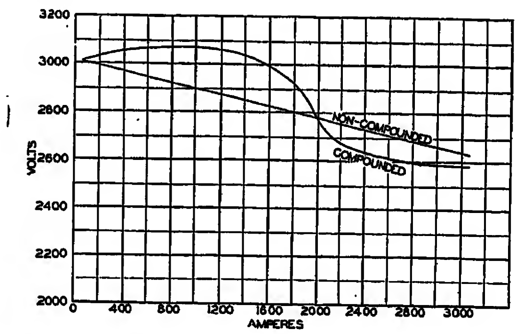


Fig. 25—Regulation Curves of Rectifiers for D. L. & W. R. R. Electrification

MERCURY ARC RECTIFIER UNITS INSTALLED OR ON ORDER IN THE UNITED STATES AND CANADA SINCE JANUARY 1, 1929

Purchaser	No. of sets	D-c. volt	Kw. per set	Total kw.	Control	Service	Put in service	Manufacturer
American Gas & Electric, New York	2	620	1,000	2,000	Automatic	Railway	1929	Brown Boveri
American Gas & Electric, New York	2	610	500	1,000	Automatic	Railway	On order	Brown Boveri
Boston Elevated Railway	2	600	3,000	6,000	Automatic remote control	City	On order	General Electric
B. C. Electric Railway	1	575	1,000	1,000	Manual	Urban	1929	General Electric
Calgary, City of	1	575	600	600	Automatic	Railway portable	1929	Brown Boveri
Calgary, City of	1	575	1,200	1,200	Automatic	Railway	1929	Brown Boveri
Chicago & Joliet Electric Railway Co.	1	620	1,000	1,000	Automatic	Interurban	1929	General Electric
Chile Exploration Co.	1	650	1,000	1,000	Automatic	Heavy mine haulage	On order	General Electric
Columbus Railway Power & Light Co.	1	600	500	500	Automatic	Urban	1929	General Electric
Columbus Railway Power & Light Co.	1	600	500	500	Automatic remote control	Urban	1929	General Electric
Commonwealth Edison Co.	1	1,500	1,500	1,500	Manual	Railway	Being erected	Brown Boveri
Commonwealth Edison Co.	2	600	3,000	6,000	Automatic	Railway	1929	Brown Boveri
Commonwealth Edison Co.	4	625	3,000	12,000	Manual	Railway	Being erected	Brown Boveri
Commonwealth Edison Co.	1	1,500	1,500	1,500	Manual	Railway	Being erected	Brown Boveri
Commonwealth Edison Co.	3	625	3,000	9,000	Manual	Railway	On order	Brown Boveri
Commonwealth Edison Co.	3	625	3,125	9,375	Manual	Urban	On order	General Electric
Consolidated Mining & Smelting Co. of Canada	3	460/560	5,600	16,800	Manual	Electrolytic	1929	Brown Boveri
Consolidated Mining & Smelting Co. of Canada	2	650	6,500	13,000	Manual	Electrolytic	On order	Brown Boveri
Consolidated Mining & Smelting Co. of Canada	1	650	6,500	6,500	Manual	Electrolytic	On order	General Electric
Delaware, Lackawanna & Western Railroad	11*	3,000	3,000	33,000*	Manual	Railroad electrification	On order	General Electric
Delaware, Lackawanna & Western Railroad	2	3,000	2,000	4,000	Automatic remote control	Railroad electrification	On order	General Electric
Eastern Massachusetts Street Railway Co	3	600	1,000	3,000	Manual	Urban	1929	General Electric
Edmonton, City of	1	575	1,325	1,325	Manual	Railway	1929	Brown Boveri
Ford Motor Co.	2	460	1,000	2,000	Manual	Power	On order	Brown Boveri
Halifax Tramways	1	590	1,100	1,100	Manual	Railway	1929	Brown Boveri
Municipality of Milan (Italian G. E.)	1	550	1,000	1,000	Manual	Urban	1929	General Electric
Montreal Tramways Co.	1	600	2,400	2,400	Automatic	Railway	1929	Brown Boveri
Montreal Tramways Co.	2	600	1,500	3,000	Automatic remote control	Urban	Under installation	General Electric
Philadelphia, City of	2	630	2,500	5,000	Manual	Subway	Being erected	Brown Boveri
Piedmont & Northern Railway	4	1,500	750	3,000	Automatic remote control	Railroad electrification	1929	General Electric
Public Service Co. of No. Ill., Chicago	1	600	1,900	1,900	Manual	Railway	On order	Brown Boveri
Public Service Co. of No. Ill., Chicago	1	600	1,900	1,900	Automatic	Railway	On order	Brown Boveri
Public Service Co. of No. Ill., Chicago	1	1,500	1,500	1,500	Manual	Railroad electrification	1929	General Electric
Sacramento Northern Railway	1	1,500	500	500	Automatic	Interurban	1929	General Electric
Saskatoon, City of	1	575	600	600	Automatic	Railway	1930	Brown Boveri
Toronto Hydro Electric System	2	600	1,100	2,200	Automatic	Railway	1929	Brown Boveri
Union Railway Co. of New York City	1	625	1,000	1,000	Automatic	Railway	1929	Brown Boveri
City Subways of New York	7	625	3,000	21,000	Automatic remote control	Railway	On order	General Electric
Totals	78*			179,900				

*In addition one spare 3000-kw. rectifier tank (without transformer) is on order. Four of the above sets consist each of two 1500-kw. tanks operating as a unit.

MERCURY ARC RECTIFIER UNITS INSTALLED IN THE UNITED STATES AND CANADA PRIOR TO JANUARY 1, 1929

Purchaser	No. of sets	D. c. volt	Kw. per set	Total kw.	Control	Service	Put in service	Manufacturer
American Gas & Electric, New York	1	575	300	300	Automatic	Railway	1927	Brown Boveri
Calgary, City of, Canada	1	575	600	600	Semi-automatic	Railway	1928	Brown Boveri
Canadian National Railways, Montreal	1	600	1,200	1,200	Manual	Railway	1928	Brown Boveri
Chicago, North Shore & Milwaukee R. R.	1	600	1,000	1,000	Automatic remote control	Interurban	1926	General Electric
Chicago & Joliet Elec. Ry. Co	1	600	500	500	Automatic	Interurban	1928	General Electric
Columbus Railway Power & Light Co	1	600	1,000	1,000	Manual	Urban	1927	General Electric
Columbus Railway Power & Light Co	1	603	1,000	1,000	Manual	Railway	1927	Brown Boveri
Commonwealth Edison Co., Chicago	1	621	600	600	Manual	Railway	1925	Brown Boveri
Commonwealth Edison Co., Chicago	1	621	1,200	1,200	Manual	Railway	1925	Brown Boveri
Commonwealth Edison Co., Chicago	2	1,500	3,000	6,000	Manual	Railway	1926	Brown Boveri
Commonwealth Edison Co., Chicago	1	1,500	1,500	1,500	Manual	Railroad electrification	1926	General Electric
Connecticut Co., New Haven	5	600	1,200	6,000	Manual	Railway	1927	Brown Boveri
Connecticut Co., New Haven	2	600	1,200	2,400	Automatic	Railway	1927	Brown Boveri
Delaware, Lackawanna & Western R. R.	1	600	200	200	Semi-automatic	Railway	1926	Brown Boveri
Dominion Power & Transmission Co., Montreal	1	600	600	600	Automatic	Railway	1928	Brown Boveri
Duquesne Light Co	2	600	1,000	2,000	Manual	Urban	1927	General Electric
Ford Motor Co., Detroit	1	250	550	550	Manual	Power	1925	Brown Boveri
Gary Railways Co., Gary, Indiana	1	600	500	500	Automatic	Railway	1926	Brown Boveri
Lethbridge, City of, Canada	1	500	400	400	Manual	Railway	1927	Brown Boveri
Long Island R. R., New York	1	650	1,000	1,000	Semi-automatic	Railway	1926	Brown Boveri
Long Island R. R., New York	3	650	1,000	3,000	Automatic remote control	Railroad electrification	1928	General Electric
Los Angeles Railway Corp	2	600	500	1,000	Automatic	Urban	1928	General Electric
Milwaukee Electric Railway & Light Co.	3	600	550	1,650	Automatic	Railway	1927	Brown Boveri
Montreal Tramways Co	2	600	1,200	2,400	Automatic	Railway	1927	Brown Boveri
Montreal Tramways Co	1	600	1,200	1,200	Automatic	Railway	1928	Brown Boveri
H. Morgan & Co., Montreal, Canada	2	265	132	264	Manual	Power	1928	Brown Boveri
New York Edison Co	1	240/260	570	570	Manual	Power	1925	Brown Boveri
Northern Indiana Public Service Co	1	1,500	1,500	1,500	Automatic remote control	Interurban	1926	General Electric
Northern Indiana Public Service Co	3	1,500	750	2,250	Automatic remote control	Interurban	1926	General Electric
Northern Indiana Public Service Co	2	1,500	750	1,500	Automatic remote control	Interurban	1928	General Electric
North Shore Power Co., Montreal	1	600	600	600	Manual	Railway	1927	Brown Boveri
Philadelphia Rapid Transit Co	2	600	500	1,000	Automatic	Urban	1927	General Electric
Philadelphia Rapid Transit Co	3	600	1,000	3,000	Automatic	Urban	1928	General Electric
Portland Electric Power Co	2	1,350	750	1,500	Manual	Interurban	1927	General Electric
Public Service Co. of Northern Illinois	1	1,500	1,500	1,500	Manual	Railroad electrification	1927	General Electric
Southern Public Utilities Co	1	600	750	750	Manual	Railway	1928	Brown Boveri
United Traction	1	600	500	500	Automatic	Urban	1924	General Electric
Utilities Power & Light Co., Chicago	1	600	550	550	Manual	Railway	1927	Brown Boveri
Utilities Power & Light Co., Chicago	1	600	900	900	Manual	Railway	1927	Brown Boveri
Totals	60			54,184				

rating of 10,000 amperes at 650 volts are now on order for electrolytic use.

Two new features of particular interest have been developed by the General Electric Company and will be applied for the first time to rectifiers which are being constructed for the Delaware, Lackawanna and Western Railroad. These consist of a biased grid adjacent to the anodes which deionizes the vapor as the current passes through zero and materially reduces the tendency to arc-back; and compounding features, using static condensers in the compounding circuit, which give substantially flat compounding up to 150 per cent load, and incidentally materially improve the power factor of the rectifier unit. The biased grid consists of a grid located directly below the anode connected to a cylindrical insulated shield surrounding the anode. The shield and grid are energized from an auxiliary transformer in such a manner as to supply the grid with a potential of the desired phase relation to the anode potential. The [illegible] thus installed acts to deionize the vapor in the [illegible]ty of the anode each time the anode voltage decreases to zero before the anode voltage can reach a negative value.

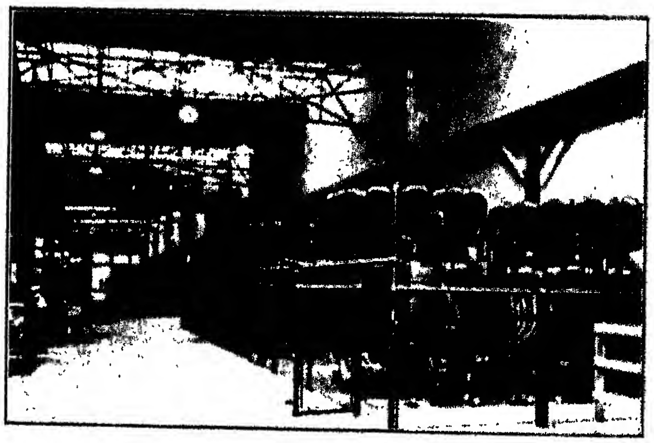


FIG. 26—THREE 5600-KW. RECTIFIER SETS (BROWN BOVERI) FOR CONSOLIDATED MINING & SMELTING CO. AT TRAIL, B. C.

The General Electric Company reports continued success with the use of the graphite anode and has

standardized on such anodes for all rectifiers. The General Electric Company has also standardized on the Mycalex Anode Seal in place of the porcelain mercury seal. On the other hand the Brown Boveri Company continues the use of metal anode for all classes of rectifiers.

The Delaware, Lackawanna and Western will use rectifiers exclusively for conversion units for its suburban electrification. Thirteen 3000-volt rectifier units with an aggregate capacity of 37,000 kw. and one spare 3000-kw. rectifier tank are now on order. These units will have a rating of 150 per cent for two hours and

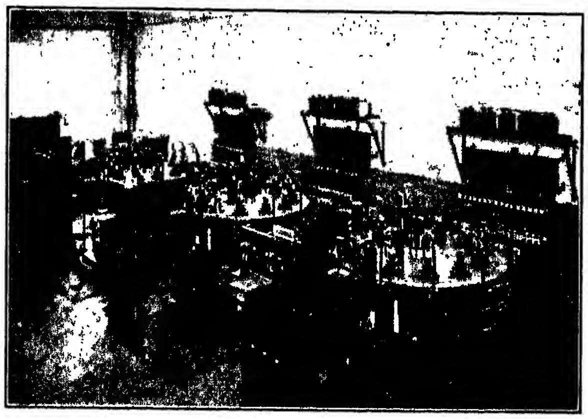


FIG. 27—THREE 1000-KW., 600-VOLT GENERAL ELECTRIC RECTIFIERS

Arranged for operation on either 25- or 60-cycle supply, installed in the Fall River substation of the Eastern Mass. Street Railway Co.

300 per cent rating for five minutes and on tests have been carried far beyond these limits.

A portable substation equipped with a 600-kilowatt 575-volt rectifier unit by Brown Boveri has been completed and put in service in 1929 by the Electric Light and Power Department of the City of Calgary.

The Board of Transportation of the City of New York has placed an order with the General Electric for seven 3000-kw. rectifiers which will be used in single unit stations to supply the new subway system. While part of the supply for the subway system will be from multiple-unit synchronous converter substations, one section of the initial line will be operated from these single-unit stations which will be installed underground, adjacent to the subway tunnel.

In Europe a 400-kw. 12,000-volt rectifier has been successful in radio transmission work and several similar high-voltage sets are now on order. Rectifiers for 2125 kilowatts 465 to 475 volts have been supplied to steel mill operation. These units were designed and built by Brown Boveri, Inc. The attached tabulation indicates the rapid growth of this type of converting equipment.

BIBLIOGRAPHY

MERCURY ARC RECTIFIERS

A. Amillac, "Electric Rectifier of the Societé Alsacienne," *Elektrotech. Zeitsch.*, Vol. 50, June 20, 1929, pp. 901.

American Institute of Electrical Engineers, Electrical Machinery Committee, *Mercury Arc Rectifiers;* with bibliography, A. I. E. E. Quarterly TRANS., Vol. XLVIII, Oct., 1929, pp. 1351-1353.

M. L. de Angeles, "Montreal Tramways Extends Use of Mercury Arc Rectifiers," *Elec. Rwy. Jour.*, Vol. 73, Aug. 1929, pp. 778-781.

E. Aubort, "Influence of Audio Frequency Harmonics of Power Circuits on Long Distance Communication Systems," (In German) *Elektrizitätswirtschaft*, Jan. 1929.

A. W. Baumgarten, "Economics of Mercury Arc Rectifiers," *Elec. Traction*, Vol. 25, Apr. 1929, pp. 190-191.

J. Blandin, "The Automatic Rectifier Substations of the Brno Tramway Co., Czechoslovakia," *Brown-Boveri Rev.*, Vol. 16, Feb. 1929, pp. 79-92.

H. C. Cocks, "Application of Alternating Current to Electrodeposition," *Elec. Rev.*, Vol. 105, July 5, 1929, p. 39.

M. L. De Angelis, "Montreal Tramways Extends Use of Mercury Arc Rectifiers," *Elec. Ry. Journ.*, Vol. 73, Aug. 1929, pp. 778-781.

Demontvignier, "Recent Progress in Glass-Bulk Mercury Vapor Rectifiers," (In French), *Soc. Belge des Elec. Bul.*, Vol. 43, Apr. 1929, pp. 110-123.

K. Fischer, "The Use of Electro-Mechanical Power Metering Devices of Normal Design for Measurements on Rectifiers," (In German), *Elektrotech. Zeitsch.*, Vol. 50, Jan. 24, 1929, pp. 113-117.

A. M. Garrett, *Automatic Mercury Rectifier Substations in Chicago*, A. I. E. E. JOUR., Vol. 48, p. 301-3., Apr. 1929; A. I. E. E. Quarterly TRANS., Vol. 48, July, 1929, pp. 925-28.

D. C. Railway Substations for the Chicago Terminal Electrification, Illinois Central Railroad, A. I. E. E. Quarterly TRANS., Vol. 48, Oct. 1929, pp. 1150-1156.

A. Gaudenzi, "Voltage Drop at the Cathode of a Mercury Arc," *Brown Boveri Rev.*, Vol. 16, Nov. 1929, pp. 303-5.

Gelber and Pleitzch, "Electrification at Mario III Mine of the Anhalt Coal Co.," (In German), *BBB Nachrichten* (Mannheim), Vol. 16, Nov.-Dec. 1929, pp. 280-283; "New Mercury Rectifier for Zinc at Tadanac," *Can. Chem. & Met.*, Vol. 13, July 1929, pp. 201 f.

A. Guenther-Schulze, "Electrical Rectifiers and Valves, (In German), *Springer*, Berlin, 1929.

L. Haffner, "Mercury Vapor Substations of the Societé Miniere et Metallurgique de Penarroya, (In French), *Rev. Gén. De L'Elec.*, Vol. 26, Nov. 16, 1929, pp. 797-801.

W. B. Hall, "Wave Forms of Mercury-Arc Rectifiers; Oscillographic Study," *Elec. World*, Vol. 93, Apr. 7, 1929, pp. 673-675.

R. M. Harvey, "An Unattended Rectifier Substation," *Elec. Engr. of Australia & New Zealand*, June 15, 1929, pp. 93-98.

G. Hauffe, "Instantaneous Photographs of a Mercury Arc Rectifier," *Ztschr. f. techn. Phys.*, Vol. 10, No. 1, 1929, pp. 23-25.

P. Hermanspann, "High-Frequency Rectifier Equipment with Automatic Regulation of the D-C. Voltage," *Ztschr. f. Hochfrequenztechn.*, Vol. 33, April, 1929, pp. 121-127.

D. C. Hoffmann, "Automatic Switching Equipment for 1500-Volt Mercury Arc Rectifier," *G. E. Rev.*, Vol. 32, Sept. 1929, pp. 466-472.

W. Hopp, "New Designs of Large-Size Glass Rectifiers," (In German), *AEG MIT.*, March 1929, pp. 75-82.

J. V. Issendorff, "Recent Investigations of the Behavior of Mercury-Arc Rectifiers, (In German), *E. T. Z.*, Vol. 50, July, 25, 1929, pp. 1078-86; *Elek. und. Masch.*, Vol. 47, Apr. 28, 1929, pp. 353-357.

L. B. W. Jolley, "Alternating-Current Rectification," 3rd Edition, *Wiley & Sons*, 1929.

H. Jungmichl, "Current Distribution in Six-Phase Rectifier Installations," (In German), *E. T. Z.*, Vol. 50, Aug. 29, 1929, pp. 1257-1262.

H. Jungmichl and R. Eichacker, "Smoothing Out the Direct

Potential in Rectifier Installations," (In German), *Siemens-Zeits.*, Vol. 9, Jan. 1929, pp. 39-50.

I. J. Kaar, "750 Kw. High-Voltage Rectifier," *G. E. Rev.*, Vol. 32, Sept. 1929, pp. 473-76.

Kleist, "Current Distribution in Rectifiers," (In German). *Ibid.*, Dec. 26, 1929, pp. 1879-1880.

E. Kobel, "Direct-Reading Vacuum Gauge for Mercury Arc Rectifiers," *Brown Boveri Rev.*, Vol. 16, Oct. 1929, pp. 281-284.

N. Kotschubey, "Alternating Current Galvanometer used as Pressure Indicating Instrument for Mercury-Arc Power Rectifiers," *Brown Boveri Rev.*, Vol. 16, Dec. 1929, pp. 331-32.

"Rockfield Rectifier Substation of the Montreal Tramways," *Ibid.*, pp. 337-340.

Chr. Kraemer, "New Twelve-Phase Transformer Connection for Large Rectifiers, (In German), *E. T. Z.*, Vol. 50, Feb. 28, 1929, pp. 303-305.

"Modern A. E. G. Ironclad Power Rectifiers," *A. E. G. Mitt.*, No. 3, Mar. 1929, pp. 85 f.

Micheluzzi, "Heavy-Current Rectifiers and the Automatic Rectifiers of the Vienna Municipal Power Plant," (In German), *Elek. und Masch.*, Vol. 47, Feb. 17, 1929, pp. 129-137.

Nowag, "The Use of Large Rectifiers for Electrolytic Work," (In German), Fachbericht-Sonderheft, *V. D. E.*, 1929.

A. Siemens, "Mercury-Arc Rectifiers of S. S. W., (In German), *E. T. Z.*, Vol. 50, Jan. 10, 1929, pp. 60-61.

P. Toulon, "Rectifier of High Power," (In French), *Rev. Gén. de l'Elec.*, Vol. 25, March 30, 1929, pp. 477-482, 518-526.

L. J. Turley, *Automatic Mercury-Arc Power Rectifier Substation on the Los Angeles Railway*," A. I. E. E. Quarterly TRANS., Vol. 48, Jan. 1929, pp. 58-66.

L. Vellard, "Substations of the Paris-Vierson Ry.," *Rev. Gén. de l'Elec.*, May 11, 1929.

O. M. Ward, "Maintenance Problems with Mercury-Arc Rectifiers," *Elec. Rwy Jour.*, Vol. 73, March 23, 1929, pp. 471-473.

A. Zastrow, "The Influence of Rectifiers on Long Distance Telephone Systems," *Elektrizitaetswirtschft*, Vol. 28, p. 35.

Report of Committee of Amer. Ry. Eng'g. Assoc., "Mercury Arc Rectifiers," *Proc. A. R. E. A.*, Vol. 30, 1929, pp. 465 f.

W. E. Warner, "Mercury Arc Rectifier Uses," *Power House* (Toronto), Dec. 5, 1929, p. 23.

"Large Mercury Arc Rectifiers," (In French), *A. C. E. C.*, Jan.-Mar. 1929, pp. 24-40.

"Mercury-Arc Rectifiers for the Berlin Suburban Railways," *Engng.*, London, Vol. 128, Dec. 20, 1929, pp. 819-820.

"Mercury Arc Rectifiers in Railway Installations Installed or on Order Since 1927; A Tabulation," *Elec. World*, Vol. 94, Aug. 24, 1929, p. 373.

"Metal Vapor Rectifier with Condensation Chamber," (In German), *Bergmann Mit.*, Vol. 7, Aug.-Sept. 1929, pp. 222-223.

"New Mercury Rectifier for Zinc at Tadanac," *Can. Chem. & Met.*, Vol. 13, July 1929, pp. 201-202.

"Oerlikon Mercury Rectifier Equipment," *Bul. Oerlikon*, June 1929, pp. 435-438.

"Railway Rectifier Stations," (In German), *A. E. G. Mit.*, March 1929, pp. 95-102.

The same in English in *A. E. G. Progress*, Vol. 5, Sept. 1929, pp. 285-290.

"Rectifier Plants for Light and Power," (In German), *A. E. G. Mit.*, March 1929, pp. 87-94.

"Mercury Rectifiers in Railway Service," *Electrical News* (Toronto), Dec. 15, 1929, pp. 45-47.

E. Kobel, "Tests with a High A-C. Voltage on a Movable Mercury Probe in a Mercury Arc," *Brown Boveri Rev.*, Vol. 17, No. 2, Feb. 1930, pp. 84-88.

E. Orlich, "Rectification of Large Alternating Currents," (In German), *Ibid*, pp. 122-126.

"Portable Steel-Enclosed Mercury Arc Rectifier," *Elec. World*, Jan. 18, 1930, p. 156.

R. Thury, "Transmission of Power Over Long Distances by Means of High-Voltage Direct-Current," (In German), *Elektrotech. Zeitsch.*, Vol. 51, 1930, pp. 114-122.

Electric Welding

ANNUAL REPORT OF COMMITTEE ON ELECTRIC WELDING*

To the Board of Directors:

Your Committee on Electric Welding hereby reports the following activities and developments in its field of activity for the fiscal year May 1, 1929 to May 1, 1930.

Meetings and Papers

The committee arranged for a symposium on welding which was held on the afternoon of Thursday, January 30, 1930 at the Winter Convention of the Institute held in New York. This symposium comprised a total of five very interesting papers:

1. *Cathode Energy of the Iron Arc*, by Gilbert E. Doan of Lehigh University.
2. *Calorimetric Study of the Arc*, by P. E. Alexander of the Thomson Research Laboratories.
3. *Resistance Welding*, by B. T. Mottinger of Akron, Ohio.
4. *Electrically Welded Structures Under Dynamic Stress*, by Morris Stone and J. G. Ritter of East Pittsburgh, Pa.
5. *Electric Welding by the Carbon Arc*, by J. C. Lincoln of Cleveland, Ohio.

The first two papers brought forth a great deal of discussion, and should undoubtedly stimulate other scientific investigators to carry on the work begun by these authors so that our knowledge of the physics, chemistry, etc., of the welding arc will eventually be completed, resulting in better welding work being accomplished in the future. The fourth paper likewise brought forth discussion and should serve as a stimulus to others to investigate particularly the behavior of welded joints and structures under dynamic loading, to determine the fatigue resistance of such joints, materials, and structures. The fifth paper brought out some very interesting information and leads one to believe that during recent years, the carbon electrode process of arc welding has not been given the consideration of which it is evidently worthy.

American Welding Society Activities

The American Welding Society issued three noteworthy pamphlets during the year covering:

1. Fusion Welding and Gas Cutting in Building Construction.
2. Welding Definitions and Symbols.
3. Revised Welding Manual.

The first publication is so arranged as to permit its being incorporated bodily into existing building codes for the various cities so that the use of welding as a means of shop fabrication and field erection may be applied to structural steel construction on a formal and recognized basis. The second publication sets forth rational definitions and terminology which will be of great help to the welding industry in standardizing and simplifying the production of drawings and designs for welding construction. The use of this work will also assist the industry to understand and adopt the use of welding much more quickly and accurately than would otherwise be the case. The third publication completes a set of four instruction manuals which are available either singly or in complete manual form on the subjects of Resistance, Thermit, Arc Welding and Cutting, and Gas Welding and Cutting. These publications cover their subjects thoroughly and are of great value, especially to industrial plants and to shops which are not thoroughly versed in the various processes.

Commercial Activities

Buildings. During the year, the Southern California Edison Company has had under way a 12-story, 3600-ton office building which will be approximately 25 per cent arc welded. All of the wind bracing and the seismic bracing for this building is to be of welded design.

The Boston Edison Company is erecting an arc welded 15-story, 1600-ton office building which is rather a unique departure in that the shop fabrication is to be carried on by riveting and the field erection by welding.

One widely known construction company has recently stated in public announcements over its signature that it is ready to bid at competitive prices on welded construction as an alternative to riveted construction on any steel buildings.

Another interesting piece of construction work completed during the year is that of the Forest Lawn Memorial Park Mausoleum at Glendale, California, completed by the Pacific Iron and Steel Company of Los Angeles. The particular feature of interest in this building is the heaviest all-welded truss that has been produced to date, namely, one weighing 60 ton, with a span of 96 ft. and a height of 18 ft. The weight of the entire welded structure is 123 ton.

A new contribution to the building art was announced by the American Institute of Steel Construction at its Seventh Annual Convention at Biloxi, Mississippi, last November. This was the develop-

*COMMITTEE ON ELECTRIC WELDING:

A. M. Candy, Chairman,

C. A. Adams,	H. M. Hobart,	A. M. MacCutcheon,
P. P. Alexander,	C. J. Holslag,	B. T. Mottinger,
C. W. Bates,	C. L. Ipsen,	J. W. Owens,
Alexander Churchward,	J. C. Lincoln,	William Spraragen.
	Ernest Lunn,	

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

ment of a new type of arc welded steel floor construction known as the "battledeck" type which was demonstrated by the erection of a sample structure automatically arc welded. This particular design of floor structure, involving steel-plate material tying beams together, is expected to be revolutionary in its effect on building construction work and to produce a less expensive total structure.

Pipe Welding. The use of welding in the construction of pipe and the field construction of pipe lines has been extended rapidly during the past year along the lines that have become pretty thoroughly standardized. No particularly new developments have been made in this field.

Pressure Vessels. Probably the most interesting development in this field is the issuance by The A. S. M. E. of Code Revisions for Pressure Vessels. These are proposed for adoption by the A. S. M. E. Code for the Construction of Unfired Pressure Vessels. The proposed changes include the following provisions: for longitudinal seams double V, butt welded, 8000 lb. per sq. in.; for girth or head seams of the single V, butt type, 6500 lb. per sq. in.; for double full fillet lap or girth welds 7000 lb. per sq. in.; and for spot or intermittent girth or head welds, 5600 lb. per sq. in. The above permissible fiber stress values can be used when the welded vessel is welded in accordance with the recommended procedure for fusion welding of pressure vessels given in the Appendix; the strength of the joints may be calculated on a maximum unit working stress (s), at right angles to the direction of the joint.

Machinery Construction. The large manufacturers of electrical equipment have made a greater proportion of their machinery of welded construction during the past year than ever before. This same practise is being taken up by manufacturers of other lines of equipment. One phase of machinery construction which has been received with particular interest is the construction of jigs, fixtures, and special shop machine tools by the welding process. It has proved to be of great economic advantage not only from a first cost standpoint but also because the manufacturer is able to tool up much more quickly than is possible with the use of cast structures.

Ship Construction. The Truss-Weld Barge Corporation launched an 8000-barrel capacity gasoline tanker, 134 ft. long and of all-welded construction.

The Electric Boat Company at Groton, Connecticut, has completed a 100-ton cargo-deck barge 118 ft. long by 10½ ft. wide of the all-welded Ewertz patented design. In the construction of this barge, 150 tons of steel were used and approximately 18,000 linear ft. of welding was performed requiring about 3500 lb. of welding wire.

The Fore River Yard of the Bethlehem Shipbuilding Corporation delivered two colliers, 350 ft. long each, with the transverse seams of their tank tops welded and with bulk heads wherein two rows of rivets were replaced by one row of rivets and a continuous weld.

The Charleston Dry Dock and Machine Company completed a 120-ft. oil tanker, and at the Standard Steel Shipbuilding Corporation, Los Angeles, a 65-ft. yacht was completed by the arc welding process. Two merchant ships, the *Morro Castle* and the *Oriente*, were constructed at the plant of the Newport News Shipbuilding and Drydock Company, for the Atlantic Gulf and West Indies Navigation Company. The outstanding new applications on these ships are the completely welded inboard shaft alley bulk heads, masts, and bilge keels.

Resistance Welding. The use of resistance welding equipment in industry at large and especially in the automotive field has gone forward rapidly within the past year.

Other developments involve the use of this type of welding for the rapid production under commercial conditions of standard steel piping. However, these developments are still in the experimental stage.

Miscellaneous

Non-Destructive Tests of Welds. Within the past year great advances have been made in methods for the non-destructive testing of welds. In general these come under three heads:

1. X-ray.
2. Stethoscope.
3. Electromagnetic.

1. X-ray. The improvement in X-ray apparatus and technique during the past few years has brought this method of examination into the commercial field, and although its application is as yet confined to fairly simple structures, it is bound to prove immensely valuable in many of the applications of autogenous welding.

2. Stethoscope. Due to the personal equation of the testing operator, this method is somewhat limited in its applications, and yet in certain cases, it is surprising how sensitive it is to moderately small defects. Not much can be stated regarding its commercial possibilities as it is still in the experimental stage.

3. Electromagnetic Methods. (a) Alternating current. This is essentially a differential method, that is, a comparison of the parent metal with the weld. These two portions are subjected to identical alternating current m. m. f., and the two secondary voltages resulting are opposed to each other, the residual being first amplified and then observed by means of an oscillograph. Experience shows that in certain simple cases, such as tubes or bars of uniform section, the characteristic indications of the oscillograph show changes of metallographic structure, such as grain size, strain, and decarbonization, as well as mechanical defects of porosity inclusions or fissures.

This method is also somewhat limited to fairly simple

structures, but in these cases gives an immense amount of valuable information.

(b) Direct current. In this case a very large direct current is passed through the welded joint and a little exploring device moved longitudinally along the joint. The exploring device is so arranged that when it strikes a magnetic field transverse to the joint, an e. m. f. is induced. The only magnetic field transverse to the joint is that due to a longitudinal component of the current which in turn will be produced only when the main or transverse current is deflected by means of some defect in the joint.

In some cases the main current contacts can be moved along the joint at the same time and at the same speed as the detector device; but the principle is the same. As in the other case, this device cannot be readily applied to all types of structures.

Practically all these devices may be applied to some of the simpler and more important types of structures; combined, they constitute a very important advance in the welding art.

During the past year the use of automatic arc welding of several different forms has increased rapidly and industry as a whole is becoming cognizant of the advantages of machine produced welds where the nature of the work is such that the necessary tooling is economically warranted.

Certain improvements in generating equipment have also been made, but these require too much detail to be discussed in this report.

Summary

There are numerous other individual welding applitations which might be mentioned but we believe that che above summarizes the principal activities in the welding field and will indicate the rapid and increased use that is being made each year of various forms of welding and welded products.

Electrophysics

ANNUAL REPORT OF THE ELECTROPHYSICS COMMITTEE*

To the Board of Directors:

Progress in the application of results in the domain of physics has been so rapid of late that there is a temptation to make the general statement that the pure physics of one quarter century becomes the engineering of the next. This, of course, would not be true in all domains of physics, but it is more or less valid in those with which the electrical engineer is most closely connected. The mounting number of uses for devices and phenomena discovered some years ago, for example the vacuum tube, photo-electricity, and the piezo-electric vibrations of crystals, is an apt illustration of the transfer from abstract interest to practical utility. It is, then, quite to the point for the electrical engineer, in forecasting and preparing for the developments of the future, to look to the electrophysics of the present day.

The physicist is continuously acquiring increasing clarity of view in connection with principles already to some extent applied. A better understanding of the present viewpoints with regard to these principles may also be of value to the engineer in further applications.

Keeping these two ideas in view, the present report does not confine itself to applied physics. In fact, the material in the first portion of the report, giving a general idea of the developments along the forefront of theoretical and experimental physics, may not find application for a long time to come (although this might also have been said of the advance line of physics many times previously, and belied by subsequent events). Following this general survey, the progress in particular topics of more immediate practical consequence, is summarized. The subjects thus discussed are: dielectrics, magnetism and magnetic materials, the conduction of electricity in solids, photoelectricity, thermionics, the cold discharge, vacuum tubes, gas discharges, the propagation of electric waves, and magnetic and electrostatic fields.

THE "FIRST LINE" OF PHYSICS

Spectacular advances in the various fields of electrophysics have been few during the past year, as they are in any year, but a great deal of serious, accurate, and quantitative work has been recorded in almost every subdivision.

The wave-like qualities of negative electricity were established beyond all reasonable doubt, more than two years ago; but though the recent demonstrations of electron-diffraction by crystals and ruled gratings can scarcely be said to have strengthened a case which was already unassailable, some of the photographs of diffraction-rings and diffraction-fringes published during the past year are so beautiful that they merit special mention (G. P. Thomson, Rupp, Eisenhut, Debye). A beginning has already been made in turning them to practical use in the study of thin films (G. P. Thomson, *et al*). Diffraction of electrons by liquids has been proved experimentally (Debye). The wave-like qualities of positive electricity have been demonstrated (Dempster), though as yet the evidence falls far short, in beauty and in clarity, of that available for negative electricity—a circumstance not to be wondered at, considering the difficulties of the experiments. Finally, the corresponding proof has been achieved for neutral matter (helium and molecular hydrogen, by Stern; atomic hydrogen, by T. H. Johnson). More and more it becomes evident that wherever there are particles, there are waves also; particles are guided by waves, waves are the carriers of particles.

The classical theory of electric conduction in metals, the theory, that is to say, that a metal contains an electron-gas, prevented from escaping by a potential-drop at the surface, was revived some three years ago with a modification, to wit, the substitution of the Fermi distribution-law for the Maxwell distribution-law as applied to the corpuscles of the electron-gas. Later it was modified in another way: by introducing, from wave-mechanics, the idea that the electron-gas can leak out gradually across the potential-drop even though this is so high that no electron within the metal has enough kinetic energy to surmount it. The combination of these two new ideas is being tested in work on the cold discharge, and on the refraction which a beam of electrons undergoes on entering a metal; they supply also a new incentive for accurate work on the photoelectric and the thermionic effect. Unfortunately, it appears that the mathematical complexities which are encountered in attempting to bring the theory closer to the experiments are very serious. Moreover, in the recent work in thermionics and photoelectrics, it is found that the influence of surface-conditions, films of foreign substances only one molecule deep, for instance, or indeed even scantier than would result from a complete covering of the surface by a monomolecular layer, is predominant. While such influences might be explained in part by invoking the second of the new ideas aforesaid, they have apparently nothing to do with the first. It is only too obvious that in these fields very much remains to be understood.

*COMMITTEE ON ELECTROPHYSICS:

O. E. Buckley, Chairman,
W. S. Gorton, Secretary,

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W. F. Davidson,	G. M. J. Mackay,	W. S. Rodman,
O. L. Fortescue,	K. B. McEachron,	J. Slepian,
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Liaison Representatives of American Physical Society
Leigh Page, W. F. G. Swann.

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In the study of discharge through gases, where the wave-like qualities of electricity play little or no part, the developments of the last year have mostly been continuations of prior work. Since recent refinements in technique make it possible to observe what goes on during intervals of the order of a hundred-millionth of a second, some interesting work on the electric spark is being published. It has been proved that the spark bursts forth so quickly, that rearrangements of space charge rather than drifting of ions must be accountable for its onset. The extensive work, both experimental and theoretical, of Compton and Langmuir and the latter's associates, upon the "plasma" or glowing gas of the arc-discharge, is being summarized and developed in articles in the *Review of Modern Physics*, the first of which has just appeared (April, 1930). Several valuable papers on the interception of electrons by atoms, the probability of ionization of atoms by electrons, and cognate subjects have appeared.

Dielectrics

The report of the Committee on Electrical Insulation, Division of Engineering and Industrial Research of the National Research Council, dated July, 1929, shows that there has recently been much activity in this field. Under the auspices of this committee, a symposium on dielectrics was held in connection with the general meeting of the American Physical Society in Washington, in July, 1929. They have also prepared a comprehensive program of research for physicists, chemists, and engineers, stressing the importance of fundamental work in solving the present difficulties due to dielectric absorption, dielectric loss, and conductivity. The situation has been summarized by Professor Whitehead, chairman of the committee (A. I. E. E. Jl., **48**, 27, 1929).

Dielectric breakdown has been discussed in many papers. Halbach (*Arch. f. Elekt.* **21**, 535, 1929) has tested various solids and differentiates between two types, the so-called electric breakdown and breakdown by heat. Moon and Norcross (*Jl. Frank. Inst.* **208**, 705, 1929) have discovered and investigated a third type of breakdown. Inge and Walther (*Arch. f. Elekt.* **22**, 410, 1929 and **23**, 279, 1930) have extended their investigations on breakdown to liquids, and considered the effects of time, of application of voltage, and of the homogeneity of the field on both solid and liquid materials. Jost (*Arch. f. Elekt.* **23**, 305, 1930) has also considered the effect of time on the strength of various solids. Smurow (*Arch. f. Elekt.* **22**, 31, 1929) determined the breakdown field for sulfur in solid, liquid, and gaseous form. A general review of the breakdown of liquid insulators has been published by Gyemant (*Phys. Zeit.* **30**, 33, 1929).

In several papers (*e.g., Zeit. f. Phys.* **56**, 446, 1929 and *Zeit. f. Tech. Phys.* **11**, 81, 1930) Böning has given experimental support to the idea that dielectric breakdown in solids of colloidal origin is affected by ions adsorbed on the inner surfaces of channels. A similar but more elaborate theory has recently been put forward by Murphy and Lowry (*Jl. Phys. Chem.* **34**, 598, 1930) to explain absorption and loss in such materials. This was based in part on previous work on textiles with various electrolyte and moisture contents, the electrical properties of which have been determined by Murphy, Williams, and Walker (*e. g., Jl. Phys. Chem.* **33**, 509, 1929, and A. I. E. E. Trans. **48**, 568, 1929). The effect of moisture in air condensers has been investigated by Lemmon and Kouwenhoven (A. I. E. E. Trans., Vol. 49, July 1930).

Ionization in paper-insulated cables has been studied further by Dawes and Humphries (A. I. E. E. Trans. **49**, 766, 1930) and also by Brown (*Jl. I. E. E.* **67**, 968, 1929). Whitehead and Marvin (A. I. E. E. Trans. **49**, 647, 1930) have found that in a high grade paper-insulated condenser the loss can be fully accounted for by dielectric absorption. Benedict (A. I. E. E. Trans. **49**, 739, 1930) has similarly calculated the power loss from the d-c. characteristics, and investigated the effect of frequency on the charging current and energy loss in various condensers. Owen (*Phys. Rev.* **34**, 1035, 1929) determined calorimetrically the heat loss in a fiber condenser at radio frequencies and found that it is proportional to the voltage and the square of the frequency. The absorption or damping of radio wave-trains in dielectrics has been discussed by Kreutzer (*Zeit. f. Phys.* **60**, 825, 1930).

The power losses in glass have been measured by McDowell and Begeman (*Phys. Rev.* **33**, 55, 1929) as a function of temperature and frequency. The variation of the dielectric constant and power factor of rosin and castor oil with temperature and frequency was found to be qualitatively in accordance with the Debye theory by Kitchin and Müller (*Phys. Rev.* **32**, 979, 1929 and Jl. A. I. E. E. **48**, 281, 1929). Goldhammer and Sack (*Phys. Zeit.* **31**, 224, 1930) studied the anomalous dispersion in dilute solutions where the Debye theory is more nearly applicable, and found results in agreement with the theory. The law of superposition in hard rubber has been confirmed by Race and Campbell (*Phys. Rev.* **34**, 1031, 1929). Electric polarization was observed by Güllner (*Arch. f. Elekt.* **22**, 141, 1929) in gypsum but not in mica nor in any glasses, indicating that the mechanism of the process is different in different substances.

Various experimenters have measured conduction currents as dependent on voltage, time and temperature. A review of previous work in relation to the theories of conduction and diffusion in solid dielectrics, has been made by Jander (*Zeit. f. angew. Chem.* **42**, 462, 1929). Experiments on quartz and rock salt have been made by Goldhammer (*Zeit. f. Phys.* **57**, 173, 1929), on rock salt and gypsum by Salessky (*Zeit. f. Phys.* **52**, 695, 1928), on an artificial resin by Suckow (*Arch. f. Elekt.* **22**, 104, 1929), and on oil by Whitehead and Marvin (A. I. E. E. Trans. **49**, 647, 1930) and by

Nikuradse (*Arch. f. Elekt.* **22**, 283, 1929). Nasledov and Sharavskii (*Ann. d. Phys.* **3**, 63, 1929) have observed the ionizing effect of X-rays by measuring the conduction current in ceresin.

Some of the most fundamental work during recent years is reported in the book "The Physics of Crystals"[1] by A. Joffe.

As in many years past, much of the work in molecular structure as deduced from measurements of dielectric constants, centers around the Debye theory. An excellent review of this subject is given by Debye himself in his recent book "Polar Molecules"[2] to which reference should be made for the fundamentals as well as for the interpretation of the results obtained before 1929. More recent reviews, with special reference to the results for aliphatic compounds and for inorganic and aromatic compounds are those by Smyth (*Chem. Rev.* **6**, 549, 1929) and by Williams (*Chem. Rev.* **6**, 589, 1929), respectively. All of the phases of the subject are treated in papers in the *Leipziger Vortrage*[3] edited by Debye.

Values of electric moments, on which to base atomic and molecular models, are perhaps best determined by studying the effect of temperature on the dielectric constants of gases. Under these conditions the molecules are least affected by neighboring molecules; and it is possible also to separate the moment produced by the distortion of the molecule by the field, from the permanent moment characteristic of the molecule when no disturbing field is present, the latter being the more desirable datum. This method, based on the relation derived by Debye in 1912, has been applied by Sänger and Steiger (*Helv. Phys. Acta* **2**, 130, 1929 and **2**, 411, 1929), by Zahn (*Phys. Rev.* **35**, 848, 1930), and by Schwingel and Williams (*Phys. Rev.* **35**, 855, 1930), to a large number of organic and inorganic compounds. Interesting among these are N_2O, CO_2, CS_2, and SO_2 which have zero moments, indicating that the three atoms in each molecule have a symmetrical linear arrangement. Measurements of the Kerr effect and the scattering of light have been used to determine electric moments by Wolf (*Zeit. f. Phys. Chem.* **3B**, 128, 1929), by Stuart, Briegleb, and Wolf (*Zeit. f. Phys. Chem.* **6B**, 163, 1929), and by Stuart (*Zeit. f. Phys.* **55**, 358, 1929 and **59**, 13, 1929). This work is based on that of Raman and Krishnan (*Phil. Mag.* **3**, 713, 1927).

The dielectric constants and refractive indexes of many binary liquid mixtures have been studied by Smyth and his co-workers, and by Williams and his co-workers. These data permit a determination of the electric moment by a third method, using Debye's theory.

There have been many more determinations of the electric moments of various compounds and groups of compounds, and discussions of the structures based on these determinations. For these papers the reader is referred to *Science Abstracts*.

Magnetism and Magnetic Materials

The fundamental nature of ferromagnetism has been discussed in many papers during the year. Slater (*Phys. Rev.* **35**, 509, 1930) has recently developed the theory of the origin of ferromagnetism which had already been treated by Heisenberg and by Bloch (*Zeit. f. Phys.* **57**, 445, 1929), based on the "interaction" of electrons as pictured on Schrödinger's theory. He discussed the relation between ferromagnetism, electrical conduction and cohesion in metals. The experiments of Dorfmann, Jaanus, and Kikoin (*Zeit. f. Phys.* **54**, 277, 1929) on the Thomson effect in nickel indicate that the same electrons are responsible for conduction and for ferromagnetism. Fowler and Kapitza (*Proc. Roy. Soc. Lond.* **124A**, 1, 1929) applied Heisenberg's theory to the phenomena of magnetostriction and of the large change in specific heat and in volume at the magnetic transformation point.

Becquerel and de Haas (*Proc. Roy. Soc. Amst.* **32**, 578, 1929) have experimentally verified the relation between paramagnetic susceptibility and temperature which is predicted by the quantum theory and which is different from that derived on classical assumptions. The quantum theoretical calculation of the paramagnetic susceptibilities of the elements of the rare earth and iron groups has been improved by Van Vleck and Frank (*Phys. Rev.* **34**, 1494, 1929). Gans (*Naturwiss*, **18**, 184, 1930) has reported that at very high fields the saturation value of magnetization of permalloy decreases, due to diamagnetism. Forrer (*Jl. Phys.* **1**, 49, 1930) has investigated the ferromagnetic and paramagnetic properties of a series of alloys near the magnetic transformation temperature.

A number of papers deal with the change of resistance of metals in a magnetic field; these include measurements by McKeehan on permalloy (*Phys. Rev.* **35**, 657, 1930), Vilbig on iron, nickel and steel (*Arch. f. Elekt.* **22**, 194, 1929), Kapitza on about thirty metals in very high fields (*Proc. Roy. Soc. Lond.* **123A**, 292, 1929), and Meissner and Scheffers on gold at very low temperatures (*Phys. Zeit.* **30**, 827, 1929).

Another attempt has been made, this time by Stearns (*Phys. Rev.* **35**, 292, 1930), to detect a change in the X-ray reflecting powers of ferromagnetic materials when they are magnetized. Although the sensitivity of the test is greater than ever before, the result is again negative and indicates that ferromagnetism should be identified with the spinning electron.

The average size of the discontinuities in magnetization (Barkhausen effect) have been determined by Bozorth and Dillinger (*Phys. Rev.* **35**, 733, 1930). Preisach (*Ann. d. Phys.* **3**, 737, 1929) has confirmed the earlier work of Bozorth in showing that practically the whole change in magnetization takes place discontinu-

1. McGraw-Hill, 1928.
2. Chemical Catalog, 1929.
3. S. Hirzel, Leipzig, 1929.

ously, and has also shown that the size of the larger discontinuities may be greatly changed by tension and torsion.

The properties of single crystals of ferromagnetic materials have again been the object of several researches. Kaya has found that in cobalt the hexagonal axis coincides with the direction of easy magnetization (*Tohoku Rep.* **17**, 1157, 1928). Potter has prepared a single crystal of a Heusler alloy and studied its structure by X-rays, as well as its magnetic properties. Iron and nickel crystals have been studied further by Foster (*Phys. Rev.* **33**, 1071, 1929), Gries and Esser (*Stahl und Eisen* **49**, 879, 1929), Sizoo (*Zeit. f. Phys.* **57**, 106, 1929), and Zeigler (A. I. M. E. Pub. No. 273 C 43, 1930). The sharp corners in the magnetization curve originally reported by Gerlach have been accepted as real by Sizoo and by Gries and Esser, but questioned by Foster and Bozorth (*Nature* **125**, 525, 1930).

Thin films of iron, cobalt, and nickel, deposited on non-magnetic supports, have been investigated by Howie (*Phys. Rev.* **34**, 1440, 1929) and by Tyndall and Wertzbaugher (*Phys. Rev.* **35**, 292, 1930). Howie explains many of the results of previous investigators as due to the relative thermal expansions of the films and their supports on which they were deposited at temperatures other than that at which their magnetic properties were measured.

The magnetic moment of some ferromagnetic atoms have been found to be greater in some alloys than in the pure metal. Weiss, Forrer, and Birch (*C. R.* **189**, 663, and 789, 1929) have shown again that this occurs in iron-cobalt but not in cobalt-nickel alloys. Constant (*Phys. Rev.* **34**, 1217, 1929) has shown it to occur in platinum-cobalt alloys and Kaya and Kussmann (*Naturwiss* **17**, 995, 1926) in manganese-nickel alloys.

The magnetic properties of Heusler alloys, as related to their crystal structure, have been further elucidated by Valentiner and Becker (*Zeit. f. Phys.* **57**, 283, 1929) and by Doerum (*Avh. Oslo.* No. 10, 1929) as well as by Potter as mentioned above.

Reviews of many of the aspects of magnetism have been written by Gerlach (*Jl. Phys.* **10**, 273, 1929) and by Bruninghaus (*Rev. Gen. Elec.* **25**, 197 and 237, 1929). A small important book, "Magnetism,"[4] describing the theoretical significance of the facts of dia-, para-, and ferro-magnetism, has recently been published by Stoner.

ELECTRICAL CONDUCTION IN SOLIDS

Conduction in solids plays a part in practically all problems with which the electrical engineer has to deal, but no entirely satisfactory explanation of the phenomenon is as yet at hand. The theory of metallic conduction which seems to promise most has been developed by Sommerfeld, and is summarized by Darrow in the *Physical Review* Supplement, Vol. 1, 1929, p. 90; by Samuel in the *Electrotechnische Zeitschrift,* Vol. 50, 1929, p. 1481; and by Houston (including his own contributions) in A. I. E. E. TRANS. **49**, 30, 1930, p. 795. Houston, in the *Physical Review*, Vol. 34, 1929, p. 279, showed how a law for the dependence of resistance on temperature could be obtained from the theory.

The marked decrease in resistance as the temperature of − 273 deg. cent. (0 deg. K.) is approached may at some future time be the key which will allow us to discover the nature of conduction. Bloch (*Zeit. f. Physik.* **59**, 208, Jan. 2, 1930) considering theoretically both the energy changes and the scattering of the electrons as they collide with the atoms of the metallic crystal, found that the electrical resistance at very low temperatures should vary as the fifth power of the absolute temperature. This is checked by experimental results only moderately well, and Bloch attributes the lack of closer agreements to the imperfection of the theoretical assumptions made in his derivation.

The phenomenon of superconductivity (a drop to extremely low resistance in the immediate neighborhood of the absolute zero) is of especial interest. De Haas, at the University of Leyden, who published much on this subject during the year, found that certain alloys, having constituents that were not superconducting, were themselves superconducting. Kapitza (*Proc. Roy. Soc.* **123**, 342, 1929) and Bartlett (*Nature* **123**, 869, 1929) also have discussed superconductivity.

Kapitza (*Proc. Phys. Soc. Lond.* **123**, 292, 1929) and Meissner and Scheffers (*Phys. Zeit.* **22**, 826, 1929) have studied the changes in electrical conductivity in strong magnetic fields. Bloch (*Zeit. f. Phys.* **53**, 216, 1929) has applied the quantum mechanics to this general problem; his conclusions are criticised by Frank (*Zeit. f. Phys.* **60**, 682, 1930). Auwers (*Naturwiss.* **45**, 867, 1929) has also treated the problem theoretically.

With regard to the conductivity of crystals, Smekal (*Zeit. f. Phys. Chem.* 3B, 162, 1929) brought forward more evidence in favor of his point of view that ionic conduction takes place at the boundaries of rifts in the crystal and that electronic conduction occurs inside the crystal. His theory has been hotly contested by Jost, many papers being published in the *Zeitschrift für Physik* and in the *Zeitschrift für Physikalische Chemie.* A list of titles is found in Jost's latest rejoinder in the latter journal for March, 1930.

Thin films have been technically applied as high resistances (*Perucca*, C. R. **189**, 527, 1929 and *Ann. d. Phys.* **4**, 252, 1930; and Kruger, *Zeit. Tech. Phys.* **10**, 495, 1929), and also as fuses (*Jl. Sci. Inst.*, **6**, 102, 1929). Ingersoll and Hanawalt (*Phys. Rev.* **34**, 972, 1929) investigated the conductivity of evaporated and sputtered nickel films. They found in the sputtered films a large gas content, which was liberated at 300 to 400 deg. cent., at which temperature the films became magnetic and better conducting. The gas content of the evaporated films was less. Braunbek (*Zeit. f. Phys.* **59**, 191, Jan. 2, 1930) applied some old results of Volmer

4. Methuen, London, 1930.

and Estermann and found that the specific resistance of a mercury layer condensing on a glass surface decreases with the amount on the surface very rapidly at first, and then more slowly, to a constant value.

Schottky and Deutschmann (*Phys. Zeit.* **30**, 839, 1929) studied the potential distribution in a copper oxide rectifier.

Herzfeld (*Phys. Rev.* **34**, 791, 1929) has published an article on the influence of surface conditions and space-charge on the conductivity of poor conductors, which may repay study.

Photoelectricity

Photoelectricity received a marked impetus during the year through the growing importance of the applications of the photoelectric cell. Among the major fields of applications may be mentioned the talking moving pictures, color television, and two-way television, the latter two achieved during 1929 and 1930 respectively; and television broadcasting which is being quite extensively developed.

Very material increases in the sensitivities of photoelectric cells have been brought about by the formation of composite surfaces, or compounds of the photosensitive alkali metals previously employed, on the cathodes of the cells. More sensitive cells of this nature (such as those obtained with sodium and potassium on the cathode) were used in daylight television and in the wire television developments referred to above; they were reported on by Olpin (*Phys. Rev.* **33**, 1081, 1929). Cells utilizing caesium as the alkali metal have been produced by Koller (*Phys. Rev.* **33**, 1082, 1929, and *J. O. S. A.* **19**, 135, 1929) and by Zworykin and Wilson (*J. O. S. A.* **19**, 81, 1929). The type described by Koller (Cs O) seems to respond more strongly to light at the extreme long wavelength limit of the visible spectrum than does any other cell at present known. Campbell and Ritchie have written a valuable book, "Photoelectric Cells,"[5] dealing at length with their construction and operation.

Passing from the technical to the scientific side of the subject, it is certainly necessary to note the study of the long wavelength limit of thin alkali metal films, made by Ives and Olpin (*Phys. Rev.* **34**, 117, 1929). This limit depends on the thickness of the film; and the highest wavelength that it reaches, as the thickness of the film is varied, was found by these authors to coincide with the first line of the principal spectrum series of the free atom, corresponding to the resonance potential. Suhrmann and Thiessing (*Zeit. f. Phys.* **55**, 701, 1929), Campbell (*Phys. Zeit.* **30**, 537, 1929), and Fleischer and Teichmann (*Zeit. f. Phys.* **61**, 227, 1930) also studied these thin films, being interested especially in potassium adsorbed on platinum. Lawrence and Linford gave a paper before the American Physical Society, April 25, 1930, on the influence of intense electric fields on the photoelectric behavior of such films.

5. Isaac Putnam and Sons.

Thermionics

The past year has witnessed no outstanding developments in that branch of electrophysics which deals with the emission of positively and negatively charged particles from heated bodies.

Many years ago Richardson developed a fundamental relation between the saturation electric current due to the emission in question and the absolute temperature. This law in its mathematical expression was $i = A\,T^2 e^{-b/T}$, where A and b were thought to be material constants independent of T. There has been in the intervening years much discussion and argument as to just what values A and b should or do have, especially for electron emission. During the past year, Fowler (*Proc. Roy. Soc.* **A 122**, 36, 1929) considered the value of A for electron emission from the standpoint of the new statistics; and Zwikker (*Phys. Zeit.* **30**, 578, 1929) tried to establish a linear relation between log A and b for surfaces of a metal with differing degrees of contamination.

Wahlin (*Phys. Rev.* **35**, 653, March 15, 1930) and Smith (*Phys. Rev.* **35**, 381, February 15, 1930) have both continued work on the emission of positive ions from hot metallic filaments.

The efficiency of an electron emitter, such as the filament in a vacuum tube, may be rated in milliamperes of electrons furnished per watt of heating energy. It has been found that, over a range of temperatures, thin films of so-called "active" metals are more efficient thermionically than metals in bulk. Filaments based on this result are used in practically all vacuum tubes as the source of electrons, and are for that reason the subject of much study. Thus the thermionic and other properties of thorium films on tungsten were investigated by Andrews (*Phys. Rev.* **33**, 454, 1929), by Reynolds (*Phys. Rev.* **35**, 158, January 15, 1930) and by Brattain (*Am. Phys. Soc.*, April, 1930). The Richardson constants of thin film cathodes formed by distillation were obtained by Espe (*Zeit. f. Tech. Phys.* **10**, 489, 1929). Becker (*Phys. Rev.* **34**, 1323, 1929) published the results of an extensive series of experiments on Wehnelt (Ba O, Sr O) oxide coated filaments; he found that the high activity is due to a thin film of metallic barium or strontium on the surface of the oxides, and that this metallic barium or strontium was produced by electrolysis of the oxides. Riemann and Murgoci (*Phil. Mag.* **9**, 440, March, 1930) found a parallelism between the variations, during the life of each oxide-coated cathode, of the electrical conductivity and of the thermionic emission. On the technical side a new core (Konel) for this latter type of filament has been introduced by the Westinghouse Company; and there were articles on the development of such oxide-coated filaments by Hodgson, Harley and

Pratt (*Jl. I. E. E.* **67**, 762, 1929) and by McNabb (*J. O. S. A.* **19**, 33, 1929).

The statistical variation in thermionic emission leads to minute erratic changes in the currents obtained from devices employing the emission. These minute changes are known under the name "shot effect." Williams and Huxford have recently studied the shot effect for positive ions. Williams and others attribute a portion of the fluctuations in electron space current from Wehnelt cathodes at low potentials, such fluctuations being larger than those for metallic emitters, to the presence of positive ions. Smith has also studied the modification of the shot effect for electrons by positive ions.

Auto-Electronic Discharge

The "pulling out" of the electrons by high fields is a source of great worry to the designers of high voltage vacuum tubes, and probably enters into most high voltage discharge phenomena. A number of papers have been published during the past year on the subject. Bridgman's note in the *Physical Review*, Vol. 34, 1929, p. 1411, is an interesting analysis of the phenomenon. Houston (*Phys. Rev.* **33**, 361, 1929) applied the methods of wave mechanics to the problem of the dependence of the effect on temperature. Millikan and Lauritsen investigated the same subject (*Phys. Rev.* **33**, 598, 1929), finding the electron-emission to be independent of temperature up to 1100 deg. K. De Bruyne was of the opinion (*Phys. Rev.* **35**, 172, Jan. 15, 1930) that no temperature variation at all had been proven as yet. He also considered the effect of contaminating layers of caesium and of nitrogen on tungsten (*Proc. Camb. Phil. Soc.* **25**, 347, 1929), and Gosling, Fowler, and Stern were others who studied this case. (*Proc. Roy. Soc.* 1929 and *Proc. Camb. Phil. Soc.* **25**, 454, 1929).

Vacuum Tubes

There is a number of different angles from which one may view a vacuum tube. It may be considered merely as a piece of apparatus, an instrument which performs certain functions; it may be looked upon as an addition to (and sometimes a considerable complication of) an existing electrical circuit; or the various physical phenomena involved in its design, manufacture, and operation may be studied. It is probably from the last mentioned standpoint that the justification for including the subject in "electrophysics" would originate. Little apology is needed, however, because of the widespread interest in vacuum tubes and their applications, and the intimate relationship to previous topics discussed and the one to follow.

The latter part of 1928 and the whole of 1929 proved a noteworthy period in the development of the type of apparatus commonly known under the generic term of "vacuum tubes." Foremost in importance was probably the development of hot cathode tubes containing gases at pressures of 0.001 mm. to several cm. The presence of this amount of gas is so much the predominant feature in the action of the tube that this division of the subject may best be discussed under "Gas Discharges" (see below).

In the case of true vacuum tubes, considering the smaller ones first, developments have been along the line of multi-grid tubes. The pentode or three-grid tube in both the space-charge screen grid and the screen grid plate shielding grid circuits, has received attention, and a space-charge grid tube with the space-charge grid co-planar with the control grid has been developed. This latter tube has low plate resistance, combined with a high undistorted output, and appears to be a very important development (Pidgeon and McNally, *Proc. I. R. E.* **18**, 266, Feb. 1930). The field of small vacuum tubes as a whole was marked by increasing stringency in the requirements of the circuits in which they were used.

Large power tubes which deliver as much as 100 kw. have been made and operated in broadcasting sets. A double-ended power tube for short waves, 15 meters, is being used in the transatlantic radio service.

Tuve, Breit, and Hafstad have succeeded in constructing a vacuum device consisting of a number of electrodes in cascade which withstood 1,400,000 volts between extreme terminals (*Phys. Rev.* **35**, 66, January 1, 1930).

Among the papers published on vacuum tube designs and circuits were:

1. "Effect of End Losses on the Characteristic of Filaments of Tungsten and Other Materials," Langmuir, McLane and Blodgett, *Phys. Rev.* **35**, 478, March 1, 1930.
2. "Calculation of the Characteristics and Design of Triodes," Kusunose, *Proc. I. R. E.* **17**, 1706, 1929.
3. "Microphonic Improvements in Vacuum Tubes," Rockwood and Ferris, *Proc. I. R. E.* **17**, 1621, 1929.
4. "Noise in Vacuum Tubes and the Attached Circuits," Llewellyn, *Proc. I. R. E.* **18**, 243, February, 1930.
5. "Output Power Obtained from Vacuum Tubes of Different Types," Pidgeon and McNally, *Proc. I. R. E.* **18**, 266, February, 1930.
6. "Circuit Analysis Applied to the Screen Grid Tube," Nelson, *Proc. I. R. E.* **17**, 320, 1929.
7. "Mathematical Theory of the Four-Electrode Tube," Brainard, *Proc. I. R. E.* **17**, 1006, 1929.
8. "Equivalent Circuits of a Triode," Chaffee, *Proc. I. R. E.* **17**, 1633, 1929.
9. "Modulators from a Physical Viewpoint," Peterson and Llewellyn, *Proc. I. R. E.* **18**, 38, January, 1930.

A new journal, *Electronics*, published by McGraw-Hill, was started in April, 1930, to take care of this subject and of thermionics and photoelectricity.

Gas Discharges

The understanding of the physical characteristics of gaseous conduction has been advanced by a number of theoretical and experimental researches during the year.

J. J. Thomson (*Phil. Mag.* **8**, 393, 1929) has worked out new formulas for the cathode fall of potential, length of dark space, and current density in the electric discharge through gases. He has shown that radiation, as well as collision, plays an important part in discharge phenomena. Brown and E. E. Thomson have found that the potential gradient in the cathode dark space is very nearly uniform.

The effect of positive and negative space charges in the gas and at the electrodes has been made more clear by work done by Langmuir. Langmuir and Tonks (*Phys. Rev.* **34**, 876, 1929) have discovered and studied a very high frequency oscillation in the electron atmosphere of an ionized gas, called by them "plasma" oscillation. This oscillation is responsible for the abnormally high electron velocities observed by Langmuir in such a gas.

The total ionization produced by an electron has been measured again by Kulenkampff and by Eisl. The latter, claiming the highest accuracy yet attained, finds for the average amount of energy lost by an electron per ion produced in air the value 32.2 ± 0.5 electron volts.

The mechanism of recombination of ions and electrons has been discussed in the light of present day knowledge by Loeb and by Seeliger. One of the most interesting discoveries of the year was made by Bergen Davis and A. H. Barnes (*Phys. Rev.* **35**, 217, Feb. 1, 1930) who find that electrons and α-particles combine only when the electrons have one of certain definite velocities with respect to the α-particle. These results, which have attracted wide attention, are still under debate.

The study of the Ramsauer effect, the abnormally small apparent area of certain molecules to slow electrons, has been continued by Brüche, Kollath, Holtsmark, Jones, Ramsauer and others.

By means of a Langmuir probe Nottingham (*Jl. Frank. Inst.* **207**, 299, 1929) has measured the potential distribution in a copper arc, with interesting results; while Mackeown has considered arcs theoretically on the basis of certain simplifying assumptions.

The ignition and form of spark in a large number of combustible gas mixtures has been studied by Tereda and collaborators (*Sci. Papers*, Inst. of Phys. and Chem. Res., Tokyo). The activation of nitrogen by electric discharge has received a good deal of attention, and a number of papers is devoted to the synthesis of compounds by cathode rays or by the glow discharge. Brewer and Westhaven (*Jl. Phys. Chem.* **33**, 883, 1929), for instance, found that the synthesis of ammonia is initiated by the positive ions in the discharge.

The importance of metastable atoms in affecting sparking potentials in noble gases has been brought out (Penning, *Zeit. f. Phys.*, 1929). Electrons are freed from electrodes by the impacts of metastable atoms and thus strongly influence currents to electrodes in ionized gases (Uyterhoven, *Phys. Rev.*, Ratner, *Proc. Nat. Acad.*, Oliphant, *Proc. Roy. Soc.*, 1929).

The manner of extinction of alternating current arcs is being actively studied. The efficacy of the oil breakers is said to be due to the generation of gas from the oil and the rapid mixing with the arc (Slepian, A. I. E. E. TRANS. **49**, 421, 1930). Improved utilization of oil as a deionizing means has been achieved (Baker and Wilcox, A. I. E. E. TRANS. **49**, 431, 1930). Gas blasts have been effectively used as deionizing means in high voltage circuit interrupters (Biermann, *E. T. Z.*, 1930).

The discharges started by high voltage surges have been the subject of considerable work such as that of Lee, Rogowski, McEachron and Goodwin, Lissner, and Berger. Both Rogowski and Beams have found that the time lag in such discharges is extremely short, so short that according to von Hippel and Franck (*Zeit. f. Phys.*, 1929) the Townsend theory of the initial glow discharge cannot apply in these cases. Paavola, under not very different conditions, finds good agreement with the story of Townsend. Lawrence and Dunningham (*Phys. Rev.*, 1930) believe that early development of very high temperatures, with possible thermal ionization, is also indicated.

In the case of lightning discharges, a considerable mass of data must be accumulated over a period of time before we shall have conclusive proof of the voltage range of induced surges and of those due to the main or auxiliary branches of direct strokes.

While much development has been reported in the applications of gaseous conduction, only a few which present outstanding novelty and promise will be mentioned.

The importance of gaseous tubes with hot cathodes is increasing rapidly. Thus the hot cathode mercury vapor tube described by Hull, (A. I. E. E. TRANS. **47**, 798, 1928) is rapidly displacing the kenotron in practise due to superior performance and lower cost. Gaseous tubes in which the starting of the current is controlled by a grid are finding almost countless applications in control work of all types. The thyratron, developed by Hull, and the grid glow tube, developed by Knowles, are of this type.

A higher-power arc rectifier has been developed by Toulon, in which the arc takes place in air at atmospheric pressure. The arc is initiated each cycle by a timed spark, and the device is called the pilot-spark rectifier.

A daylight lamp in which part of the light comes from the arc between a mercury surface and a hot tungsten filament has been described by Strickland.

PROPAGATION OF ELECTRIC WAVES

Continued progress has been made during the past year in the study of the propagation of short waves. Long time echo signals having delays up to 4 minutes 20 seconds have been reported by Hals, and a number of other observers have found echoes with time lags up to 30 seconds. Observations by Galle and Talon during

the solar eclipse of May 9 (reported in *C. R.*, Jan. 6, 1930) were carried out at a wavelength of 25 m., several other investigators have used wavelengths of the order of 30 m. A low group velocity as the cause of long time echoes has been considered by a number of authors; thus Breit has shown that if the refractive index of the Kennelly-Heaviside layer decreases exponentially with height it is possible that this effect would be produced (*Proc. I. R. E.* **17**, 1508, 1929). In this explanation, absorption is tentatively ignored, an assumption which many workers regard as unjustifiable. Pederson believes that echoes having a greater delay than ten seconds cannot be due to waves propagated entirely within the earth's atmosphere, and concludes that echoes with delays up to one minute are probably due to propagation along or reflections from "Störmer bands" of electrons within the magnetic field of the earth, while echoes with greater delay must be due to bands of ions located so far away as to be beyond the influence of the earth's magnetic field (*Proc. I. R. E.* **17**, 1750, 1929).

Renewed interest has been shown in theoretical and experimental investigations of the surface wave (ground wave), particularly that which is set up near short-wave transmitting antennas. Considerable attention has also been given to the "optical" properties of the earth for wavelengths in the radio spectrum.

American and European investigators have collected many data which throw light on the propagation of short waves, such as diurnal variations in layer height, effect of magnetic storms, and short-time echo signals over both long and short distances of transmission. An interferometer method of measuring slight changes in the optical path of waves reflected by the ionized region in the upper atmosphere has been devised by Hafstad and Tuve (*Proc. I. R. E.* **17**, 1786, 1929).

Magnetic storms are accompanied by severe disturbances in short wave transmission. It has been found that at such times the height of the Kennelly-Heaviside layer is materially increased. This has been attributed to unusual solar activity at such times. Several investigations to determine the correlation in greater detail are under way.

Abroad, particularly in Germany, there has been great activity in connection with very short waves from a few centimeters to ten meters in length. Methods of generating and modulating relatively large amounts of power in this range had been devised and the propagation properties of the waves studied. It is found that these waves follow substantially an optical path between transmitter and receiver, that the attenuation in space is very low, but that the ground wave is absorbed with extreme rapidity. The sky wave is unaffected by fog, rain, sunlight, or darkness.

In addition to the large amount of experimental work on short wave propagation, progress has been made in the study of the ionized regions above the earth from the point of view of the physics of the upper atmosphere. Notable in this connection is the work of Hulbert and others in the Naval Research Laboratories.

Electromagnetic Theory; Electric and Magnetic Fields

A thoroughgoing discussion of the electromagnetic theory is found in "The Electromagnetic Field" by Mason and Weaver. Leigh Page says, "It constitutes unquestionably the foremost critical study of electromagnetic theory in the English language."

Heisenberg and Pauli (*Zeit. f. Phys.* **56**, 1, 1929) and Oppenheimer (*Phys. Rev.* **35**, 461, March 1, 1930) are continuing their researches on remodeling the fundamental theory. Kaplan and Murnaghan also published an article, quite mathematical in nature, "On the Fundamental Constitutive Equations in Electromagnetic Theory" in the *Physical Review* for April 1, 1930.

Passing to a much less abstract phase of the subject, namely, to waves on wires, there is an interesting treatment of propagation along wires from this standpoint by Aguillon in *Annales des P. T. T.* Vol. 17, 1928, p. 846, and Vol. 18, 1929, p. 89. Karapetoff discussed a *Graphical Theory of Traveling Waves between Parallel Conductors* in the Jl. of the A. I. E. E. for February, 1929. Ohashi (*E. N. T.* **6**, 1, 1929) considered the "Disturbing Effect of Traveling Waves and the Mutual Influence of Telegraph Lines," taking the lines to be both inductively and capacitatively coupled.

The experimental study of traveling wave phenomena on transmission lines has been advanced by the use of truck mounted cathode ray oscillographs and portable impulse generators, rated at 1,000,000 volts. Much work done along this line was reported in several papers at the Midwinter Convention.

Closely allied to the paper by Ohashi mentioned above is a large number treating disturbances in one electric line due to another—or to waves from a distance. Among these may be mentioned:

1. "Electrostatic Influence of a Power Line on a Telephone Circuit," Picault, *Annales des P. T. T.* **18**, 885, 1929.
2. "Disturbances Induced in a Communication Circuit by Traction Currents," Rüdenberg, *Jl. Teleg.* **53**, 145, 169, 1929.
3. "Electromagnetische Störungen," Schindelhauer, *E. N. T.* **6**, 231, 1929.
4. "Mutual Inductance Measurements on Conductors with Earth Return," Klewe, *E. N. T.* **6**, 467, 1929.
5. "Analysis of Irregular Motions with Applications to the Energy Frequency Spectrum of Static and of Telegraph Signals," Kenrick, *Phil. Mag.* **7**, 176, 1929.
6. "Power Circuit and Inductive Interference with Telephone and Telegraph Systems," Huth, *Trans. S. Af. I. E. E.* **20**, 115, 1929.
7. "Unbalance of Telephone Lines and Circuits Subject to Inductive Disturbances," Roehmann, *T. F. T.* **18**, 18, 1929.
8. "Mutual Impedance between Adjacent An-

tennas," Englund and Crawford, *Proc. I. R. E.* Aug., 1929.

9. "Magnetic Disturbances and Long Distance Reception," Kennelly, *Electronics*, April, 1930.

10. "Uber die induktive Beeinflussung von Schwachstromleitungen durch Starkströme," Schiller, *Arch. f. Elekt.* **23**, 217, 1929.

11. "Reciprocal Theorems in Radio Communication," Carson, *Proc. I. R. E.* **10**, 952, 1929, and an extensive commentary on the subject by Ballantine in the same issue.

Some papers which touch the power engineer probably as closely as the transmission engineer are:

1. "Distribution of Electric and Magnetic Fields," Hague, *Elec.* **102**, 185 and 315, 1929.

2. *Flux Linkages and Electromagnetic Induction in Closed Circuits*, Bewley, JL. OF THE A. I. E. E. **48**, 216, 1929.

3. *Forces on Magnetically Shielded Conductors*, Morecroft and Turner, JL. OF THE A. I. E. E. **48**, 25, 1929.

There should also be included here the series of papers which is probably familiar to many A. I. E. E. members, namely, that comprising the symposium on *Shielding in Electrical Measurements* held at the A. I. E. E. Summer Convention in 1929.

Miscellaneous

The year has seen notable advances in piezo-electric oscillators. Marrison (*Proc. I. R. E.* **17**, 1103, 1929) has developed a constant frequency oscillator of this nature that will maintain its frequency constant to within one part in 10^7 over considerable time intervals. The peculiarities of parallel cut quartz crystals, such as non-oscillating thicknesses, doublet resonant frequency, etc., have been explained on a rational basis, and quartz crystals with a zero-temperature coefficient for frequency have been obtained by using special proportions Lack (*Proc. I. R. E.* **17**, 1123, 1929).

The subject of direct current amplifiers and their application to various types of measurement has been a live one during the past year. There have been papers by Brentano (*Zeit. f. Phys.* **54**, 571, 1929), Eglin (*J. O. S. A.* **18**, 393, 1929), Carwile and Scott (*Phil. Mag.* **34**, 161, 1929), Razek and Mulder (*J. O. S. A.* **18**, 460, 1929 and **19**, 390, 1929), and Rasmussen (*Ann. d. Phys.* **2**, 357, 1929).

The application of mathematical methods to electrical engineering, especially to electrical circuits, was of interest to many. The American Mathematical Society conducted a symposium on "Differential Equations of Engineering" in December. At this meeting the question of establishing a journal of applied mathematics was discussed. Two important books dealing with circuits were "Operational Circuit Analysis" by Bush, and "Heaviside's Operational Calculus as Applied to Engineering and Physics" by Berg. Some other followers of Heaviside, with the subjects of their articles, may be noted:

1. "Heaviside's Fractional Differentiation," Sumpner, *Phys. Soc. Proc.* **41**, 404, 1929.

2. "Extension of Heaviside's Operational Calculus for Invariable Systems," Van der Pol, *Phil. Mag.* **7**, 1153, 1929.

3. "A Generalization of Heaviside's Expansion Theorem," Pennell, *Bell System Technical Journal*, **8**, 482, 1929.

4. "Operator Solution of Linear Differential Equations," Van der Pol, *Phil. Mag.* **8**, 861, 1929.

5. "Differential Equations as a Foundation for Electric Circuit Theory," Fry, *Am. Math. Monthly* **36**, 499, 1929.

6. "Operational Methods in Wire Transmission Theory," Josephs, *P. O. E. E. Jl.* **23**, 60, April, 1930.

Physics as a whole has been extending its sphere of influence into the biological sciences. In this extension, many studies are being made, on subjects such as the electrical currents developed by nerves and the electrical characteristics of cell surfaces, which may be classed under the domain of the applications of electrophysics—perhaps one might say under electrobiology. Such investigations are hopeful indications of an advance in knowledge of physical processes in this division of the sciences.

Values of the general physical constants have been published by Birge in the *Physical Review Supplement*, July, 1929. Volumes V and VI of *International Critical Tables* were also published in the past year. Volume VI contains much of interest to the electrophysicist, the table of contents including electronics and gas conduction, dielectric properties, electrical conductivity, pyro- and piezo-electricity, thermo-electricity, electrolytic electromotive forces, and magnetism.

In case the electrical engineer wishes to pursue studies in a particular field in present day physics or wishes to renew his knowledge of some branch of the science, he will find helpful summaries of the theoretical and experimental conclusions to date in a series of articles entitled "Some Contemporary Advances in Physics" by K. K. Darrow, published in the *Bell System Technical Journal*, and also in the numbers of the *Reviews of Modern Physics*. The latter periodical was started (under the name of the *Physical Review Supplement*) during the past year for the purpose of providing general surveys for those who were not specialists in the subjects discussed.

For drawing up the above summary, information has been furnished by members of the Electrophysics Committee, and in addition contributions of material have been received from Messrs. R. M. Bozorth, K. K. Darrow, J. M. Eglin, J. B. Johnson, and J. C. Schelleng. The chairman is especially indebted to Dr. J. M. Eglin for assistance in compiling the report.

General Power Applications

ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS*

To the Board of Directors:

Your Committee on General Power Applications has continued the method of keeping in touch with developments and suggestions for papers as outlined in the report last year.

Considerable progress has been made along these lines. Sixteen committee members have supplied twelve résumés of developments in fields with which they are intimately connected, and thirteen suggestions for papers have been submitted from which your committee hopes to be able to develop several for presentation at Institute meetings during the coming year.

Your committee believes that a continued development of the existing method and material will produce gratifying results.

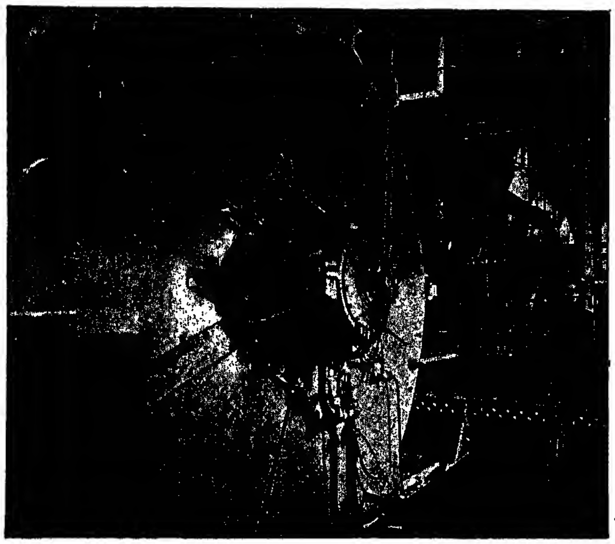

FIG. 1—TWO 8500-HP. A-C. MOTORS DRIVING THE TWIN SCREWS OF *SS. Pennsylvania*

Attention is called to the fact that no attempt has been made in the report to cover the entire industrial field. The efforts of the committee have been confined to certain outstanding industries in which it is believed developments reflect a general picture of the advance during the year.

MARINE EQUIPMENT

Steam-Electric. The year 1929 was marked by exceptional activity in the application of turbine-electric drive to large liners of our merchant marine service. There was finished or under construction at the close of the year equipment totaling 114,600-shaft-hp. capacity for six ships, aggregating over 56,000 gross ton. Progress was also made in the application of this type propulsion to smaller vessels such as coast-guard cutters, towboats, and private yachts, making a total for 17 installations for the year of 157,260 shaft-hp. This indicates an increase of 40,660 shaft-hp. or approximately 0.35 per cent over 1928.

The *SS. Pennsylvania,* commissioned during the past year, is the third vessel of this type put into service by the Panama Pacific Line of the International Mercantile Marine, and, together with the *SS. Virginia* and *SS. California,* completes, in tonnage, the largest single fleet of all-electric craft in commercial service. The new ship is very similar to the two preceding vessels, having a power plant consisting of two 6600-kw. 2880-rev.-per-min. a-c. turbine generators and twin

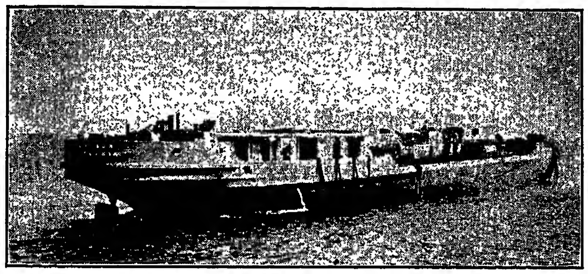

FIG. 2—THE *Seneca Sun,* A 320-HP. DIESEL-ELECTRIC TANKER OPERATING IN THE NEW YORK STATE BARGE CANAL

screws driven at 120 rev. per min. by 8500-hp. 4000-volt direct-connected motors. (Fig. 1).

Toward the close of the year, the Dollar Steamship Line announced that two ships in round-the-world service will be provided with turbine-electric drive. The driving motors will develop a total of 26,500 shaft-hp., which, from point of size and power, will make them the largest commercial vessels of this type in the United States.

The installation of turbine-electric drive was completed on the private yacht *Viking,* marking the first installation of this kind. The two driving motors are rated at 1300 shaft-hp., each with a speed of 160 rev. per min. Equipment is now under construction for a larger yacht, *The Corsair,* which will have two driving motors of 3000 shaft-hp.

A European adaptation of the turbine-electric drive is interesting to note. The exhaust from the reciprocating engines is sent through the low pressure turbine to a condenser. The alternator driven by this low-pressure turbine supplies power to a motor mounted

*COMMITTEE ON GENERAL POWER APPLICATIONS:

J. F. Gaskill, Chairman,

D. H. Braymer,	E. W. Henderson,	H. W. Price,
C. W. Drake,	P. C. Jones,	N. R. Stansel,
C. W. Falls,	A. M. McCutcheon,	E. C. Stone,
C. D. Gray,	N. L. Mortensen,	W. H. Timbie,
C. F. Harding,	D. M. Petty,	M. R. Woodward.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

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on the engine shaft and in some instances, supplies auxiliary power to the ship. This method of utilizing the engine exhaust has been found to increase the power nearly 25 per cent without any further increase in fuel.

Diesel-Electric. The year saw still wider application of Diesel-electric drive for vessels of all types. Although the total of 8595 shaft hp. is less than the total in 1928, still the number of such ships so equipped was substantially the same. Vessels with this drive include freighters, tankers, ocean tugs, river towboats, ferries and several special boats for government use. The Diesel-electric drive seems especially favored for vessels operating in sheltered waters as the majority of installations were on boats operating on our rivers or lakes.

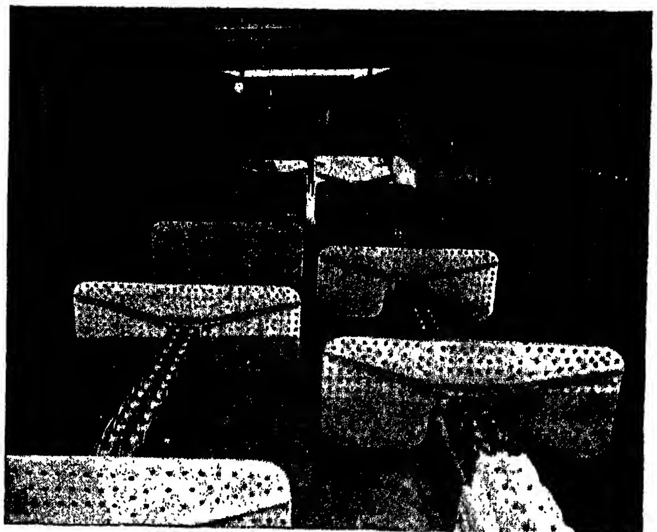

Fig. 3—Paddle Arrangement of Caterpillar Tractor Tugboat

Each set of paddles is driven by a 80-hp. motor

Fig. 4—Caterpillar Tractor Tugboat Acts as the Rudder to the Tow

The Sun Oil Company commissioned two new tankers for operation on the Great Lakes, New York Barge Canal and the open Atlantic, which are powered by Diesel engines and d-c. generators and motors. Oil engines, free from fire, are especially advantageous for tankers, while electric drive gives the flexibility so desirable in maneuvering in rivers and canals. One of these tankers, the *Seneca Sun*, is shown in Fig. 2.

The government adopted Diesel-electric drive for two survey boats, the *Liston* of the Engineer Corps and the *Hydrographer* of the Coast and Geodetic Survey. The *Liston* will develop a shaft-hp. of 350, while the *Hydrographer* has an installation capable of 650 shaft-hp. The United States Engineer Corps commissioned also two stern-wheel towboats of 150 shaft-hp. Each, for use on the Mississippi and its tributaries.

A unique application of Diesel-electric drive is shown in Fig. 3. This boat, which can operate in two feet of water, has two 100 hp. Diesel engine generator sets and two 80-hp. driving motors. Each set of caterpillar paddles has a motor so that the direction of the tug can be changed by varying the speed of the paddles. The boat, when pushing a string of barges, as in Fig. 4, acts as the rudder for the tow. This method of propulsion is especially fitted for shallow, crooked rivers and possibly may supplant the familiar paddle-wheel that has been native to these rivers for the past century.

Electric Railways[1]

Although it is understood that electrification of steam railways and traffic problems are more thoroughly covered by other committees of the Institute, several specific applications of new power devices and methods to electric railways may be briefly cited to advantage.

The influence of gasoline motor bus competition and the demand for higher speeds, greater rates of acceleration, lighter weight and less noise in operation have resulted in electric railway cars with light-weight high-speed motors, equipped with large ratio-gear reduction and differentials, the latter being similar to those of the automobile. Aluminum parts, and even whole car trucks and bodies of aluminum alloy, are being tried out.

The weight of the motor-control resistor has been reduced 75 per cent by the use of non-corrosive resistance strip ribbon, wound on edge, upon insulating tubes mounted on steel bolts in a light structural steel frame. The temperature coefficient is practically constant and local heating is eliminated by means of large radiating areas.

The excessive noise of operation, after careful noise amplified voltages have been determined from test, has been greatly reduced by means of annular iron and lead inserts in car wheels, the use of rubber annular cushions between spider and rims of such wheels and the use of non-resonant type gear construction.

1. Contributed by C. F. Harding.

A new type of control is shown in Fig. 5. During the year, 100 cars with this control were placed in service on the Chicago surface lines. In this car the electro-pneumatic control and air brakes are foot operated, while the magnetic track brakes are operated by hand. This development increases the practicability of the one-man cars.

That the gasoline-electric cars increased in popularity with the large railroad systems for operation on small branch lines is shown by the fact that a total of 63 such units were placed in service by large railroads during

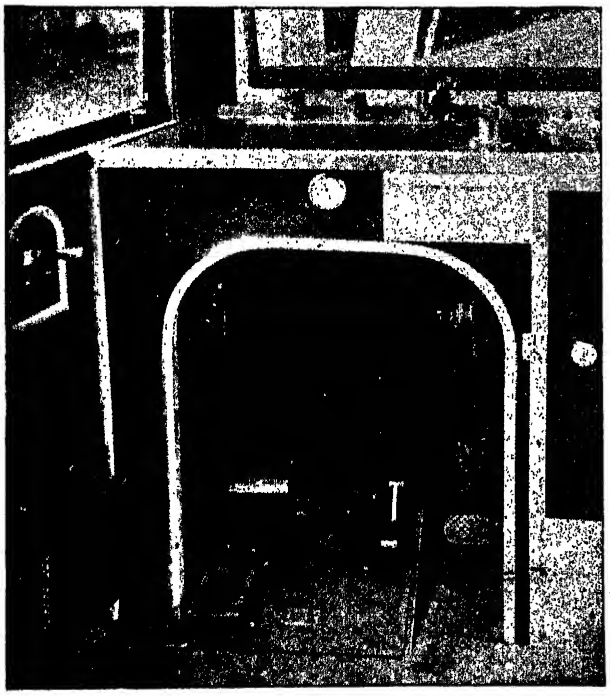

Fig. 5—Foot Control and Auxiliary Control Handles in Light Weight Car

1929. The general tendency in this equipment is toward an increase in size and total capacity in horsepower installed.

The Diesel-electric cars are newcomers in this field, four being built and put in operation during the year. Tests to date show a surprisingly low cost of fuel per mile with a reliability equal to their predecessor, the gasoline-electric cars.

The "three-power locomotive," arranged to operate from storage batteries, oil engine or third rail, is increasingly popular in the freight yards due to the unusual versatility of its power plant.

Although the substation equipment for the new Philadelphia subway included the largest 60-cycle, compound-wound, inter-pole type synchronous converters ever built, the starting circuits of which included star-delta switching on the high-voltage side of the transformers, the competitor of such converters, the mercury arc rectifier, is apparently increasing in favor and, in many installations, is showing marked economy of operation over the synchronous converter. Net annual returns as high as 25 per cent have been reported upon new investments in rectifiers, and sustained minimum efficiencies well above 90 per cent have been secured with such apparatus upon 25 per cent load factor applications. Capacity purchased has been doubled during the year and is now well over 125,000 kw. of rating. The use of load shifting and load-limiting resistors located out-of-doors in the feeder circuits has assisted greatly in maintaining continuous service. The extensive introduction of rectifiers upon our electrified steam railroads was attributed to the natural advantage which a unit with no moving parts has over one with rotating parts with wearable and friction surfaces, high efficiency with fluctuating loads, absence of noise and vibration, low maintenance expense and the elimination of extensive ventilation facilities. Fig. 6 illustrates one of these rectifiers in the substation of a western railroad.

Steam railroad electrification has received a forceful impetus during the year. The Pennsylvania Railroad, with its 21,500-kv-a. frequency-changer sets equipped with quick-response excitation, plans for the 3000-volt motor car operation on the Lackawanna Railroad, the extension of the well-proved economies of the Great Northern electrification involving unique motor-generator type locomotives hauling 700-ton trailing load on a 2.2 per cent grade, the Cleveland Union Terminal with a 17-mi. electrified right-of-way now nearing completion, and its 22 new electric locomotives each

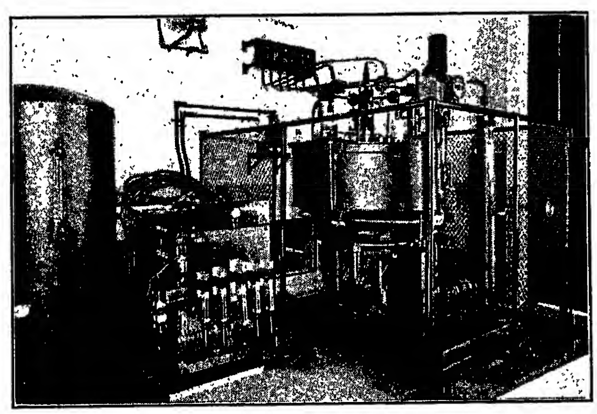

Fig. 6—500-Kw., 1500-Volt Mercury Arc Rectifier in Railroad Substation

having six twin-gear, 3000-volt, d-c. driving motors, 2900-hp. total capacity,—to say nothing of the extensive Mexican, British, and Austro-Swiss electrification developments—well emphasize the popularity, economy, and variety of electrical applications to heavy railway service.

The acceptance of radio communication between engine cab and caboose of a long freight train was evidenced by the number of installations during the year. In actual operation, advice and direction by radio have proved to be of great value in preventing accidents and saving of time.

Steel Mill Industry

The year 1929 was marked by intense activity in the iron and steel industry. Operating rates were exceptionally high and new records for steel ingot production were established. Electricity contributed a considerable part in maintaining this activity, since it is only through the flexible and easily controlled operation of the mills that such production is possible.

Accompanying this increase in production is the increase in the number of new electrical mill drives that were installed or ordered. During the year, over 325,000 hp. in main-roll drives, each 300-hp. or over, were sold. This makes a total capacity on main-roll drives of over two million and a half horsepower.

As in previous years, d-c. drives exceeded a-c. drives in number and capacity, amounting to approximately 70 per cent of the total horsepower. Especially notable increased number of reversing mill drives contracted for was the during the year. Synchronous motors continued extensively applied to constant-speed drives, while to be induction motors were used principally where fly-wheel effect was necessary. All new plants installed 60-cycle equipment while many of the older plants continued with the previously established 25-cycle standard. Several instances were noted where 60-cycle replaced the old 25-cycle machines.

Due to the rapid expansion in this industry during the year many interesting and unique applications of electric drive were made—far too many to be even briefly mentioned in a report of this size. Several specific installations have been selected and will be described, as they indicate the general trend of the progress being made in this industry.

Previous to this year blooming mills have had the upper and lower rolls driven by a single motor through a pinion stand. The new 54-in. blooming mill of the Illinois Steel Company omits the pinion stand, and the upper and lower rolls will be separately driven by two 5000-hp. reversing motors. These motors are capable of a combined emergency torque capacity of 3,940,000 lb-ft., which makes this mill the most powerful of any yet installed.

The 52-in. universal intermediate mill will be driven by a 6000-hp. main and a 2000-hp. auxiliary roll reversing motor. These motors receive power from a synchronous motor-generator set consisting of two 3000-kw. 700-volt d-c. generators, a three-phase 25-cycle 8500-hp. synchronous motor and a direct-connected exciter. This is twice the size of any previous installation using the synchronous motor-generator set instead of the customary fly-wheel and induction motor set.

The most sensational installation of synchronous motors for steel mill drive is in a billet mill and sheet bar mill of the Columbia Steel Company, Pittsburg, California. Two motors were installed in this plant, one of them is shown in Fig. 7. They are rated at 5000 hp., 82 rev. per min., 2300 volts and have a diameter of 25 ft., making them the world's largest diameter synchronous motors.

A wide strip mill installation of the Illinois Steel Company is of particular interest as it uses d-c., adjustable-speed motor drives on the roughing stand. This is the first continuous wide strip mill to depart from the previous practise of using alternating current for this drive. The drive uses 12 motors totaling more than 20,000 hp. They are equipped with generator voltage control, thus eliminating the use of starting resistors and contactors.

An unusual application of reversing mill motors is being made in the new plant of the A. M. Byers Company, Ambridge, Pa. A 1200-hp. reversing motor will drive the main 750-ton ram of a large ingot press which will compress wrought iron sponge balls into a rectangular ingot form preparatory to rolling in a blooming mill. An auxiliary 200-ton ram, used for shaping the ends, will be driven by a 325-hp. reversing motor.

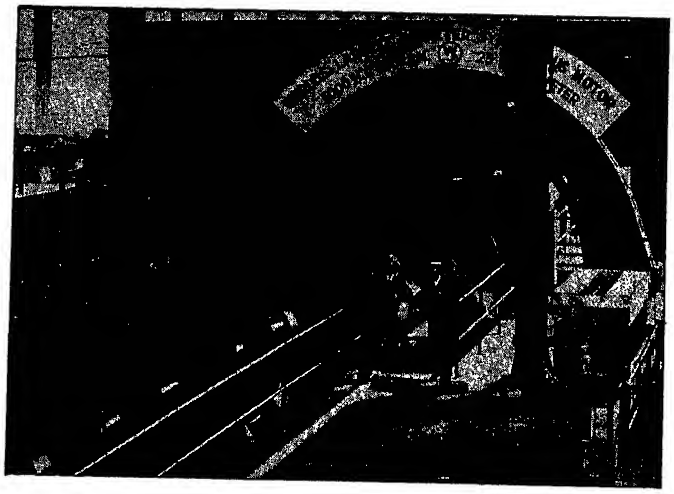

Fig. 7—A 5000-Hp. Synchronous Motor of 25-Ft. Diameter

Another example of departure from previous practise is in a new six-stand, 30-in. continuous mill which will be driven by three synchronous motors rated 2500, 3000, and 3500 hp. respectively. Heretofore continuous mills have been driven by a single motor, direct-connected or geared to a lay shaft from which the stands were driven through beveled gears. In this particular case, the three motors tie in through their synchronous speed making it equivalent to the former gearing between stands.

The first universal slabbing mill to utilize separate electric motors on the horizontal and vertical rolls was installed during the year. The horizontal rolls are driven by a 7000-hp., 50/100-rev. per min. motor and the vertical rolls by a 1650-hp., 112.5/270-rev. per min. motor. Control is so arranged that acceleration, retardation, and reversing are simultaneous and in exact speed ratio. Another outstanding characteristic of this installation is that power is supplied to the

motors from three 2400-kw. generators with their armature connected in parallel. This is believed to be the first installation to successfully utilize three generators in parallel to supply power for a reversing drive. Incidentally, the 7000-hp. reversing motor is one of the largest built during the year. Fig. 8 shows a motor of this size installed at the Youngstown Sheet and Tube Company.

Squirrel-cage motors with special stator and rotor design have been substituted satisfactorily for d-c. motors in the operation of pack furnaces. This application is new for squirrel-cage motors as very frequent starting and stopping is involved, sometimes amounting to over 150 starts per hour.

With new design for the control of the conveyer and doors on these pack furnaces it has been possible to eliminate some labor attendance. The operator of the rolling mill receiving the packs from the furnace controls the discharge of the packs by means of a foot switch while conveyer travel is automatically controlled by limit switches. Operation of the doors by means of a-c. motor drive decreases the heat loss and the amount of excessive air admitted to the furnace. The entire layout is very ingenious and tends toward better working conditions as well as better quality in furnace output.

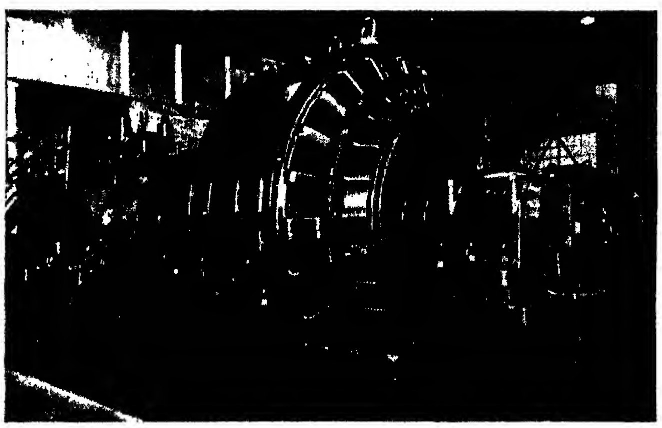

Fig. 8—A 7000-Hp. D-c. Reversing Mill Installed at the Youngstown Sheet and Tube Company

Although it is not classed under the steel industry there is an installation of a new copper mill worthy of mention, since it represents a radical departure from usual practise. The finishing stands of a continuous mill for rolling copper rods are driven by seven adjustable-speed, d-c. motors, totaling 3000 hp. This mill will deliver two strands of copper rod simultaneously, at a maximum speed of 3500 ft. per min.

Paper Industry[2]

An improvement in the drive of paper super-calenders was obtained by a variable-voltage drive for each calender. Current is supplied to the d-c. motor from a generator driven by an a-c. motor, either synchronous or induction type. To this motor-generator set is added an exciter where no direct current is available for excitation. The fields of the generator and of the calender motor are separately excited.

Speed control of the calender motor is obtained by varying the field of the generator, thus applying variable voltages to the motor armature. The motor speed being proportional to the voltage impressed on the armature, it is possible to obtain a speed range of from 50 ft. per min. to 1000 ft. per min.

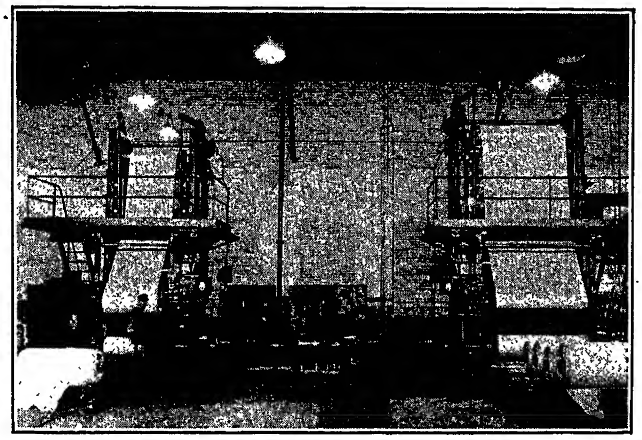

Fig. 9—Two Calenders at the Rhinelander Paper Co. with Separate Motors and Variable-Voltage Control

In stopping, which is accomplished almost instantly, the fields of the generator are reversed to a value sufficient to give a small reversed voltage. To prevent reversal, a voltage relay causes the generator field to be opened as the voltage across the motor armature approaches zero. If reversing is desired, this can readily be obtained by reversing the generator field.

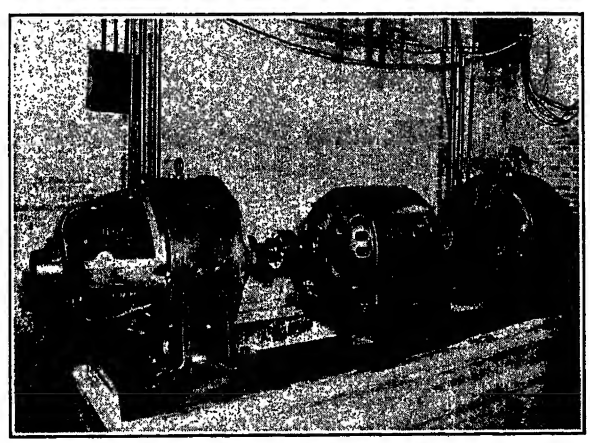

Fig. 10—Motor-Generator Set to Supply Direct Current to Calender Motor Shown in Fig. 9

Fig. 9 shows two calenders at the plant of the Rhinelander Paper Co., and Fig. 10 indicates the motor-generator set for this application consisting of synchronous motor driving two d-c. generators, one for each of the calender motors.

2. Contributed by E. W. Henderson.

One of the greatest advances in years has been the application of individual motors to the rolls of surface winders. This application not only simplified the mechanical drive but made it possible to wind rolls of paper more evenly so that they were more acceptable to the printer. Waste per roll of paper was very materially reduced by this application. The control of each roll, individually and of the slitter, was obtained electrically. A very definite indication of winding tension was secured by the use of ammeters in each motor circuit.

Fig. 11 shows an application of individual motors to a Moore and White winder.

Cement Industry[3]

In a large part of the cement industry the past year has been a period of curtailed production. Although the increase in consumption was about normal, the greater productive capacity due to the construction

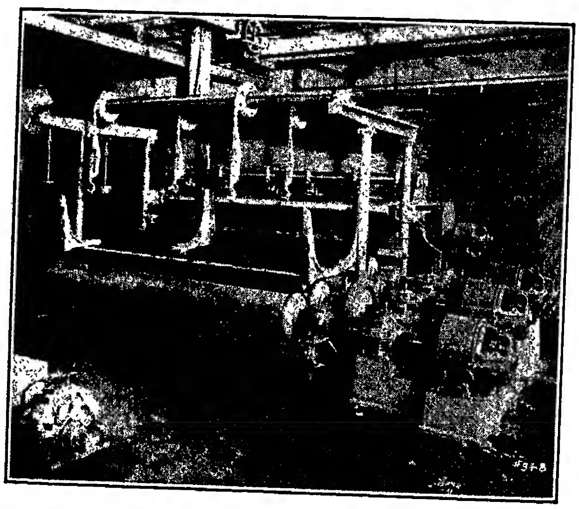

Fig. 11—A Moore and White Winder with Individual Motors for Each Set of Rolls

of new plants and improvements in old plants exceeded that growth.

While this curtailment of production has induced unusual efforts to improve operating methods, other factors influencing this situation were certain changes in the standard specifications for cement, which led many plants to modify their manufacturing procedure to permit a product that would conform to the new standards. Such changes have been accompanied by extended electrification of old mills and refinements in the electrical applications in new mills.

There has developed a marked interest on the part of central stations, in the cement mill loads and the possibility of securing mutual benefit to both the central station and the cement industry by the utilization of off-peak power. New rates have been established and others proposed which make it attractive for cement mills to adjust their operating schedules so as to increase greatly the power consumption during the off-peak hours, correspondingly curtailing the consumption during the periods of heavy load on the central stations. While the benefits that can be derived from the rates so far promulgated have not usually been sufficient to warrant the installation of additional machinery to permit taking advantage of the low cost of such off-peak power, this factor has been given consideration in designing new plants and some existing plants have been able to benefit by minor modifications in processing methods. This appears to offer a very important field for future reduction in power costs for the cement industry, as suitable adjustment of capacities for grinding equipment and storage bins will permit large blocks of power to be diverted from on-peak to off-peak periods. A collateral benefit of such changes is to be noted in the possible reduction of labor costs where one or more entire shifts can be eliminated from the operating schedule.

There has also developed during the period under consideration a trend on the part of the central stations to its benefit from tie-ins with isolated plants operating on steam produced by waste heat from cement kilns. There is a number of cement mills now connected to central stations under contracts covering interchange of power, which permits these mills to dispose of surplus power during those portions of the day that steam production from waste heat exceeds power demands, and allows the use of central station power when required in emergency. At the rates now usually offered by central stations for such surplus power, the available quantity must be considerable to warrant the installation of a substation which is ordinarily needed. It seems probable that when a more generous return is offered for this surplus power, based not only on the busbar cost to the central station, but also on the improvement in conditions which may be expected from the connection of numerous and widely scattered power sources to a large distribution system, there will undoubtedly be more cement plants which will take advantage of this interchange arrangement. The cement mills may also be justified in charging off a part of the substation and connection costs against the benefits of the emergency service, and to improvements in waste heat plant operation due to steadier load conditions. Such interchange contracts also may be made more attractive by higher allowance for the surplus power furnished during the central station peak-load hours. The mills may then curtail load during such hours, and carry the additional load on the waste heat plant during the night off-peak period when the normal mill load would also be lighter due to the shutdown of quarries and other part time operations.

The confidence of the cement industry in the possibility of profitably disposing of its excess power may be indicated by the installation during the past year of a 10,000-kw., 100 per cent power factor, 3600-rev. per min. turbo generator which will operate from a waste

3. Contributed by M. R. Woodward.

heat power plant. This is, we believe, the largest turbine operating from a cement mill waste heat plant, and the advent of units of this size with their superior economy may be looked upon as significant of probable future developments.

This apparent development of a more sympathetic attitude toward the cement mill problem on the part of those who have power to sell, offers most hopeful prospects for the future, as the load which the mill can offer is normally most attractive to the central station from the standpoint of load factor, power factor and diversity.

In the quarries and mines, the use of electrically operated well drills for primary drilling, and electric shovels for handling quarry product, is fairly well standardized. There are instances where advantage has been taken of improved shovel performance due to the use of Ward Leonard control, and there appears to be a movement towards higher voltage distribution for quarry operations. Portable cables for connecting electrically operated equipment to distribution lines are now quite generally protected with jackets of automobile tire rubber, and more attention is being given to the grounding of such quarry equipment along the lines of recent developments in connection with the grounding of portable apparatus.

In handling material to and from the stone and coal storage, it is worthy to note that there has been completed at least one grab bucket traveling crane installation having motors throughout equipped with antifriction bearings and complete automatic master switch control and electric braking systems interlocked to permit high operating speeds with minimum danger of over-travel. These refinements have been justified by the very severe duty imposed on such cranes in this industry due to the practically continuous service of twenty-four hours a day, seven days a week.

In the field of fine grinding the large motors used have been generally of the synchronous type with a marked tendency toward units developing sufficient inherent starting torque to eliminate the use of clutches, but the clutch and brake band motor have generally held their own on applications involving the starting of the heavy eccentric loads found in ball type grinding mills. On centrifugal type grinding equipment which present a balanced starting condition, there have been applications of the usual type of salient pole directly connected self-starting synchronous motors with excitation at 125 volts and normal field arrangement. With such motors the starting current is quite high and so in this field there has been some further extension in the use of a special synchronous motor which obtains the desirable high starting torque with low starting current by means of a wound secondary starting winding and external resistance control. This year for the first time, up to 250 volts have been used in the fields by means of a simple centrifugal, automatic field splitting switch built integral with the motor. Both the above applications have eliminated the use of clutches at a point where with synchronous motors their use had previously been required.

For the above applications the speeds have usually been quite low, ranging from 180 to 450 rev. per min. as the application required, but we have noted one case where eccentric tube mill loads are being started without clutches by high-speed salient-pole synchronous motors connected through gear reduction units.

In connection with kiln drives a marked inclination has developed toward closer speed regulation than is inherent in the slip-ring motors frequently used in the past for this service. This has led to the application of d-c. motors and motor-generator sets in a number of instances, but the requirement has also been very satisfactorily met by the application of the commutator type a-c. motor with speed control through the use of automatic brush shifting and a special speed regulating winding. This type of motor has not only made available practically perfect speed regulation under varying loads but has also permitted almost infinite speed adjustment over a range of about 3 to 1, as well as providing for creeping speeds. With this special motor, the efficiency and power factor also are superior to those of the slip-ring motor, and compare most favorably with the combination of d-c. motors and motor-generator sets previously such motors have been used extensively in the textile and oil industries, but their application to the cement kiln drives is of recent development with results that indicate the possibility of their more extensive use not only for kiln drives but for other applications in cement mills as well.

The effort to improve operating economies has led also to the installation of improved types of coal feeders, and has developed the necessity for much closer speed adjustment on d-c. motors driving these feeders. Closer speed regulation, which also has come to be considered an essential for this application, may lead engineers in the future to turn to the use of commutator brush-shifting a-c. motor for such applications, as such motors seem to have speed regulation characteristics superior to those available in the shunt-wound d-c. motors ordinarily used.

The synchronizing of raw material feeders with kiln speeds continues to claim close consideration and has led to the installation of Selsyn control for this purpose. Last year we reported the use of interconnected but separately excited shunt-wound d-c. motors, and this year has brought the development of mechanical interlocking of the field rheostats to provide the synchronizing of kiln and feeder motors where direct current is used for both drives.

The interlocking of various machines, and the material-conveying equipment is receiving closer attention both with the view of providing greater safety and also preventing delays from flooding elevator pits, conveyers, etc. Where such interlocks are not installed, lamp signals are commonly used, controlled by hatch-

way limit switches to indicate visually by flashing lamps the operation or stopping of elevators and conveyers.

Rubber Industry[4]

The first three-quarters of 1929, like the entire year before, was a period of expansion rather than one of incorporation of new developments and applications. New plants have been built and existing plants enlarged. Power consumption has increased, and in general, the energies of the engineering staff have been of necessity largely confined to the exigencies of growth.

One of the outstanding trends of new power applications has been the more extensive use of conveyers necessitating a modification of layouts to permit a straight line flow of normal production. The conveyer load, almost negligible a decade ago, is constantly becoming a more considerable part of the total.

For heavy drives, such as mill, refiner, and wash lines, low-speed synchronous motors continue to grow in popularity and usefulness. Although evidences of such use are not yet common, there is little doubt that the synchronous motor will find wider employment in the future for the lighter drives, since its effectiveness in maintaining high power factor on individual feeders cannot be overlooked.

One rubber manufacturer installed the geared drive

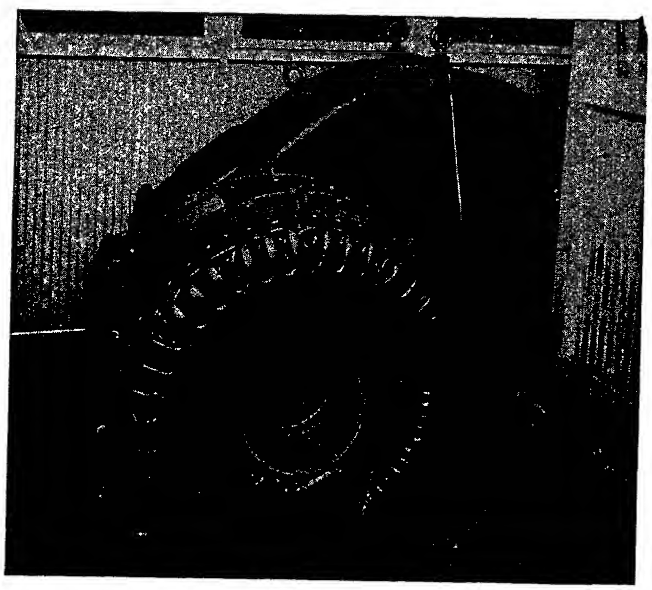

Fig. 12—Combination Motor and Gear Drive on Rubber Mill

shown in Fig. 12 instead of the customary low-speed synchronous motor. This drive consists of a high-speed synchronous motor and roller bearing helical gear built as a unit. It is interesting to note that the efficiency was increased 3.5 per cent higher than the slow speed motor and it also develops 40 per cent more starting torque with the same kv-a. inrush.

D-c. drives, at least in this industry, show no signs of decreasing. The wider use of conveyers, already mentioned, and refinements of processes, make speed control constantly more necessary, and in spite of the development of various adjustable speed motors of the a-c. type, direct current still has many attractive features for this purpose.

Automatic control is being more extensively used, and probably has not yet reached its peak. One particularly fertile field is the synchronizing of calender trains. The application of close synchronization to a series of

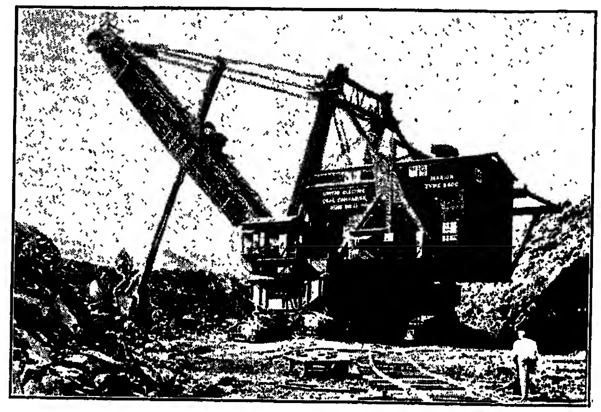

Fig. 13—This Electric Shovel has a Scoop Capacity of 15 to 20 Cu. Yd. and Weighs 1800 Ton

motors seems, in the rubber industry, to have lagged behind the progress made in comparable drives in the paper industry. This is undoubtedly due to the less stringent requirements; however, a need for better methods undoubtedly exists.

The financial crisis in the last quarter of the year has not seriously disturbed the rubber industry which is looking ahead to a year of perhaps not quite such intensive production in the early part, but a none the less prosperous twelvemonth.

Mining

Several power applications in the mining industry during the past year indicated that the progressive trend of this industry noted during 1928 is still continuing. Although two of the following applications are not new developments, they are representative of the trend because of their size either large or small.

In 1928 we reported on the use of electric shovels of 12 cu. yd. capacity in strip mines. The past year saw still further increases in the size of these shovels, so that there are now in service shovels of 15 to 20 cu. yd. capacity and weighing 1800 ton. The mammoth size of one electric shovel is clearly shown in Fig. 13.

Direct current is supplied to the various motors by an installation of one 1700-kv-a. synchronous motor driving three generators with a total output of 1660 kw. The total installed electrical hp. including all the auxiliary apparatus and transformers is nearly 4500. Despite the size of this shovel, it will make a complete digging cycle in 47 sec.

In contrast to the size of the foregoing equipment is

4. Contributed by P. C. Jones.

the new mine locomotive, Fig. 14, for operation in extremely thin coal seams which is the lowest in height of any mining engine of this weight ever built. This 6-ton locomotive is 24⅞ in. in height, which includes the trolley, and is rated at 56 hp. It runs at a speed of four miles per hour and is equipped, as a modern street car is, with series-parallel control and dynamic braking. There are two of these now operating in a mine near Huntington, W. Va.

Another development in connection with mine locomotives is the manufacture of the first practical gearless

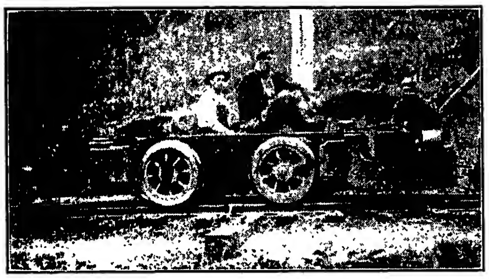

Fig. 14—Gathering Locomotive in Service at Utilities Elkhorn Corp. Mine.
Over-all height, less than 26 in.

cable reel equipment. This reel is driven direct by the armature shaft and thus revolves at the same speed as the motor armature. Roller bearings are used at both ends of the shafts, the top one being tapered.

The Consolidated Copper Mines, Kimberly, Nevada, installed a mine hoist so equipped that control can be effected from either of two mine levels or from the surface. The hoist is operated by a 900-hp., d-c. motor, with a modification of the variable-voltage system. From the time a button is pressed starting the hoist, no human governance is required as the stops and dumping are all under automatic control. (Fig. 15).

One of the largest hoist motors in the world was installed during the year. Its motor is rated at 3200 hp. 600 volts, and it will raise a skip 3000 ft. per min., from a shaft 3000 ft. deep.

A hoist application worthy of note is in the new water supply system of the City of New York. The equipment includes 16 hoists, each driven by a 250-hp. 500-rev. per min. d-c. motor, and each motor having a 350-hp. synchronous motor-generator set for its supply of energy. Control is of the semi-automatic type.

Oil Industry[5]

Pipe Line Pumping. Electric power is being used more extensively for main line pumping, especially where Public Utility Companies can supply the power without great additional expense for transmission lines, substations, etc., and consequently are able to offer a low rate for electric power.

A paper on *Electrification of Oil Pipe Lines in the Southwest,* by D. H. Levy, was read at the Dallas Regional Meeting May 1929, and printed on page 995 in the A. I. E. E. Quarterly Trans. July 1929. This paper contains comparative cost data on electric pipe line pumping by centrifugal and reciprocating pumps.

Well Drilling. There seems to be an increasing demand for electric rotary drilling rigs. Magnetic control is now being used quite extensively on the larger motor equipment, but manual control is standard on the smaller and more common sizes. As the control equipment is mounted or assembled as a unit, it can be easily moved from one well to the next. The control equipment for the mud pumps is also assembled in the same manner.

The size of drilling motors has gradually increased from the 75-hp. motor of a few years ago so that now the use of 125- and 150-hp. motors is common, and several 200-hp. equipments have been operated this year. One manufacturer has a 300-hp. motor in operation. These larger motors are required on account of the increased depth of wells; several have been drilled to over 7000 ft., and a few have reached 8000 ft. in depth. The oil well equipment companies are making designs for much greater depths which may call in the near future for motors as large as 400 or 500 hp. The motors driving the mud pumps have naturally followed the increase in size of the drilling motors.

A new development this year that is interesting is the use of electricity to heat up the heavy lubricant known as "crater compound" so that it will flow in cold weather for applying to the rotary drill bits.

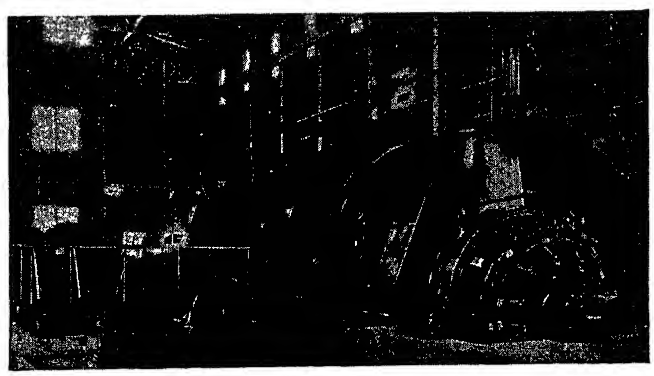

Fig. 15—This Automatic Mine Hoist can be Controlled from Either of Two Levels or from the Surface

Pumping and Pulling. To meet the demands of heavier pumping service a larger two-speed motor has been developed so that now a 35/75-hp. motor at 600/1200 rev. per min. is available in both open and protected types. Control equipment for these motors, as for other sizes, is mounted together on a single frame work so it can be easily transported to the well and installed with a minimum of field service.

Open and Protected Control Equipment. The electrical manufacturers are now able to supply gas pro-

5. Contributed by C. D. Gray.

tected control equipments for use in all departments of the oil industry. Open equipments are extensively used where the risk of explosion is small and where the expense of protected equipment would be prohibitive, but there seems to be a growing tendency toward gas protected apparatus in which partial protection is given.

There is an increasing demand for explosion-proof housings on the collector rings of slip-ring variable-speed motors which are made strong enough to resist an internal explosion and are designed to prevent the exit of hot gas that might ignite the exterior gas.

A recent development in gas protected apparatus is the housing of the drum controllers used with variable speed motor equipment. In these controllers the drum axis is mounted vertically and the contacts are made very sturdy and enclosed in a heavy steel case which is strong enough to resist internal explosion, and so designed that the temperature of any gases forced out from such explosion is reduced so much that an external explosion is prevented.

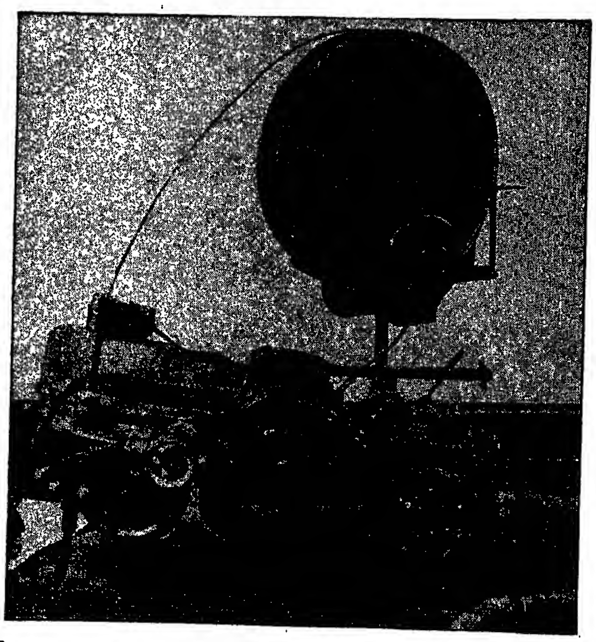

Fig. 16—Self-Propelled Automatic Arc Welder for Welding Floors, Tanks, Ship Decks, Etc.

Electric Welding[6]

The superior and more economic designs brought about by the recognition of welding as a basic manufacturing process rather than as a substitute for riveting indicate an increasingly effective utilization of the essential advantages of this art. Another outstanding sign of progress is the legal recognition of welding in building construction, as exemplified by the new law in Pennsylvania allowing welding in the construction of buildings in first class cities, and the adoption by 71 cities throughout the country of building codes authorizing this type of building construction.

An interesting example of the use of electric arc welding is the recent extension to the powerhouse of the Haddon Hall and Chalfonte Hotels of Atlantic City, where it was imperative that the work should be done quickly and quietly, without disturbing the guests in the hotels or the residents in their vicinity. This power house has a height of 134 ft. and is one of the tallest welded steel building frames in the world. The Hotel Homstead, Hot Springs, Va., is probably the highest welded steel building so far completed, having eleven stories with an over-all height of 150 ft. Another example of welded steel structure is a footbridge 846 ft. long and containing 105 tons of steel, over the Delaware and Hudson Railroad tracks in Schenectady, N. Y.

The announcement by the American Institute of Steel Construction in November, of a new type of arc welded steel floor promises to reduce the weight of buildings to such an extent that an increase of 25 per cent or more in height may be realized without increasing the weight on foundations. The new flooring utilizes steel plates and structural steel beams. The total cost of a floor constructed of 3-in. I beams and 3/16-in. plates, covered on the top with cork tile and fireproofed on the under side, is estimated by the Institute at a little over $1.00 per sq. ft., which is less than the cost of a good carpet. This "battle deck" floor is applicable to residences, multiple-story buildings and bridges, and will save from 20 to 60 lb. per sq. ft. of floor in dead weight. Fig. 16 illustrates the type of equipment used in this work.

Several thousand miles of long pipe lines have been constructed during the year 1929 by the arc welding method. Notable examples are as follows: A 714-mi. line from Port Arthur to El Paso, Texas, which carries oil at a pressure of 800 lb. per sq. in.; 425 mi. of 12-in. pipe from Cushing, Okla., to Chicago, Ill.; and a 205-mi. pipe line running from Jal, New Mexico, to El Paso, Texas, 16 in. in diameter, to carry gas for the El Paso Utilities Company.

The new vehicular tunnel under the Detroit River between Detroit and Windsor, Canada, was built on dry land in sections which were placed in position on the bottom of the river and caulked around the full circumference of the shell by the arc welding process.

The manufacturers of electric apparatus are increasingly using arc welded machine structures to replace castings. The stator for a 160,000-kw., turbo generator has recently been constructed of arc welded steel. On another page is illustrated, (Fig. 8) a 7000-hp. d-c. motor of welded construction.

It is interesting to note that 90 per cent of American made airplanes are now of welded steel construction.

The resistance welding process has been advanced and is being used for welding boilers of both the water-tube and fire-tube types. Great savings are realized when arc welding is used for repairing such machine

6. Contributed by W. H. Timbie and E. C. Stone.

parts as locomotive draw bars, broken housings, gear teeth and railroad tracks.

An outstanding example of welding making seemingly impossible repairs possible was noted in St. Joseph, Mo. A 285-ft. stack fractured 190 ft. from the base. Arc welding repaired the break which otherwise would have necessitated rebuilding the entire stack. The first complete arc welded ship, a 2500-barrel oil tanker, was recently launched at Charleston, S. C. This boat, which is 120 ft. long with a 10-ft. draft, required but nine workmen for its construction.

Industrial Heating[7]

Three-Phase Arc Furnaces. The trend this year, continued from 1928, in the use of the three-phase arc furnace for melting steel was toward larger transformers for a given physical size of furnace. However, there is no common method of rating arc furnaces so there is no way of expressing this trend, such, for example, as kv-a. per ton holding capacity of the furnace. The largest arc furnace in the steel industry has a nominal holding capacity of 80 ton and is equipped with two sets of electrodes, each set being supplied by a 10,000-kv-a. transformer. This is 250 kv-a. per ton. This furnace, installed during the latter part of 1928, has shown during this year a distinct gain in the economy of steel melting by the use of large units. A furnace now being installed for melting steel has a nominal holding capacity of 25 ton. A transformer rated 10,000 kv-a. was supplied for this furnace. This is 400 kv-a. per ton.

There is a tendency to increase the furnace voltage for steel melting furnaces. The upper limit at present is around 250 volts.

The use of multiple voltages for steel melting furnaces has increased. The general trend is towards three operating voltages for furnaces 1000 kv-a. and above.

There was a marked increase in the recognition of the importance of alloy steels during the year. This led to a revival of interest in the induction furnace for the production of this class of steel. A six-ton core type induction furnace was placed in service for remelting alloy steel scrap. This furnace is rated 800 kw., 0.40 power factor, 8.5 cycles, 220 volts, is single-phase and is supplied by a 2000-kv-a. frequency-changer set. The pouring capacity is approximately 30 ton per day of 24 hr. This is the third furnace of this type and size installed in the United States.

The coreless induction furnace made marked progress in the alloy steel industry. The standard frequency for that service is 960 cycles. The largest installation of the year consists of four furnaces which are supplied by two 300-kw. single-phase 800-volt generators, one driven by an induction motor and one by a steam turbine.

Widely different and many new applications of electric heat for heat-treatment processes were made. Some of particular interest are as follows:

Two new sizes of wire enameling ovens have been brought out that enable a wire speed considerably higher than that previously received. These ovens handle wire sizes from 18 mil to 3 mil. Each oven bakes five separately enameled coats to 16 wires. The resulting product conforms with the most rigid electrical specifications.

In the annealing of fine copper wire the discoloration due to moisture has been overcome by the use of a mixed gas atmosphere in closed steel retorts. The furnace is of the lift type and will handle 6000 lb. of work per 24 hr. day in retorts 2½ ft. in diameter by 3 ft. deep with an economy of 15 to 25 lb. per kw-hr.

One large plant is installing four large furnaces with equipment for controlling the cooling rate. Two of these are rectangular pit furnaces with a connected load of 1100 kw. capable of annealing (temperature 1500 deg. fahr.) in one charge, 50 ton of alloy steel bar stock in 25 ft. lengths. The heating and cooling cycle is completed in 24 hr.

A double-chamber car bottom furnace, each chamber rated 675 kw., is used for annealing bar stock. These furnaces are equipped for accelerated cooling, employing the same method as the pit furnaces, above which is a closed forced air circulation system that prevents the air from coming in contact with the work.

Adjustable timing devices are used to regulate an entirely automatic continuous furnace for normalizing or quenching (1500 to 1650 deg. fahr.) 6000 lb. per hr. of bar stock 23 ft. long. This furnace has a connected load of 1000 kw.

A differential drive is to be used for a flat top continuous conveyor furnace now nearing completion. A production of 600 lb. per hr. is automatically discharged through a chute in the rear. This is similar to the new standard mesh belt conveyor furnace as shown in Fig. 17, which handles 300 lb. per hr. of small steel parts to 1600 deg. fahr.

For annealing the new short-cycle malleable iron, three-elevator type furnaces are used, producing 100 ton per week. The cycle has been shortened to 24 to 30 hours. This new process reduces the inventory, eliminates boxes and packing.

A new type of continuous recuperative furnace has been introduced to the vitreous enameling industry which, due to elevating the firing chamber, has a natural effective heat seal. Recent improvement has reduced the standby losses by the introduction of a lift type refractory tile barrier between the firing and preheating chambers. This furnace shows a gross economy of 14 to 16 lb. per kw-hr. when firing steel at 1450 deg. fahr. to 1700 deg. fahr.

An important design change has been made in the large 70 ft. long, copper, hydrogen brazing furnaces for refrigerator evaporators. The greater portion of the alloy car supporting the work is now in a separate,

7. Contributed by N. R. Stansel.

enclosed chamber (except for a narrow slot) beneath the heating chamber. This has resulted in better economy, longer life of car and permits the use of a less expensive alloy for the car. There is now in use a smaller furnace of the same type which, with a connected load of 100 kw., automatically brazes 120 pieces per hr. The operator has only to place the work on the cars that carry 14 pieces, at 7-minute intervals, into the furnace.

A new pit type furnace with a simplified control equipment has been introduced for heat treating alumi-

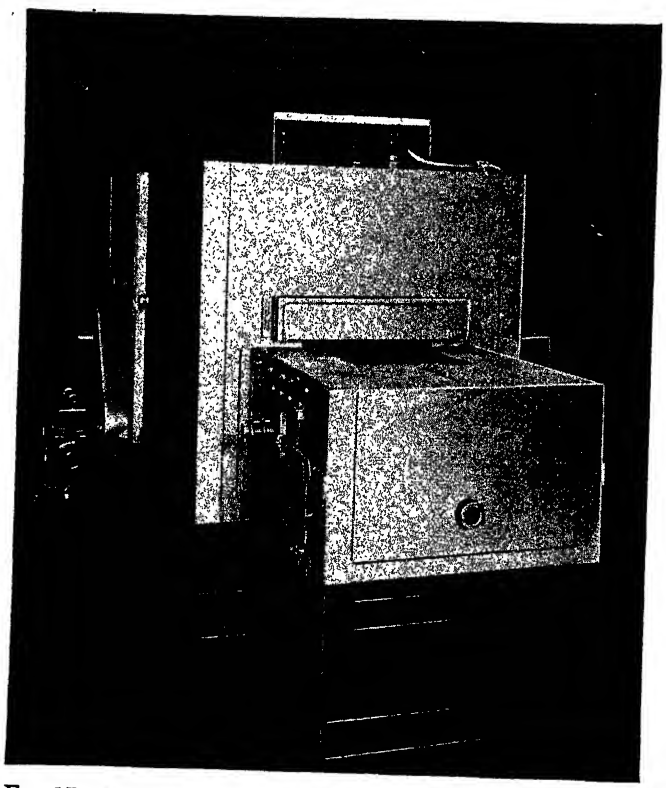

FIG. 17—45-KW. TWO-CIRCUIT MESH BELT CONVEYER FURNACE

num alloys, Fig. 18. This furnace is equipped with high heat and low heat switches which give a high power input for quick heating and low power, low gradient input so essential for the holding periods. Improvements in the cover design have reduced the losses to an absolute minimum.

Two new glass annealing lehrs have been developed for the continuous annealing of sheet glass at about 100 deg. fahr. The larger of these is 13½ ft. wide and 800 ft. long. Heating units totaling 1600 kw. are installed in the first 400 ft.

The cast-in immersion units, which have been successfully applied to heating stereotype metal with as much as 360 kw. in one melting pot, are now being applied to a cable press pot 3 ft. 2 in. in diameter and 4½ ft. deep. This pot, with a connected load of 210 kw., will be capable of melting 18,000 lb. of lead per hr.

Figs. 19 and 20 show a bell type furnace which uses gas to prevent scaling of the charge. In this particular type furnace the base remains on the floor and the bell shaped top may be removed. In this way one furnace can keep several bases busy, saving in equipment investment, material handling and heat required per charge.

The increasing use of furnaces with a controlled atmosphere has created a demand for equipment to economically produce gases suitable for this work. Development work is now being done to produce a mixed gas of hydrogen and nitrogen from ammonia. Another method is to "crack" city gas and make it suitable by breaking up the methans and causing it to unite with steam, giving a resulting mixture of carbon monoxide, carbon dioxide, hydrogen and nitrogen. A furnace for this work is in operation with a connected load of 65 kw. which delivers 1000 cu. ft. of mixed gas per hour for use in brazing furnaces. Approximately 2 cu. ft. of mixed or cracked gas are obtained from 1 cu. ft. of city gas.

ELECTRICAL CONTROL[8]

Gang control, the control by an individual at a distance of a group of electrical drives, has received much attention during the past year. Twelve motors of similar operating characteristics, design and duty cycles, may now be started by means of only two sets of control equipment. With this new interlocking control, applicable to any one of the twelve motors as frequently as is necessary for starting this particular long-hour service, it is possible to eliminate nearly all of

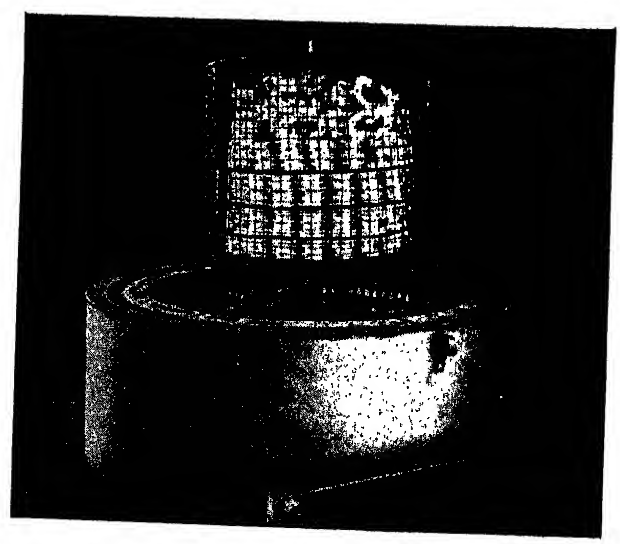

FIG. 18—84-KW. PIT TYPE ELECTRIC FURNACE FOR HEAT TREATING ALUMINUM ALLOY CASTINGS

the cost of nine complete control equipments previously considered necessary for such an installation. This system provides a method whereby either of two autotransformer starting equipments may be selectively connected to any one of twelve motors for starting purposes. This unit interlock control is entirely self-contained and is so mounted that each control section can be easily removed from the control benchboard for

8. Contributed by C. F. Harding and N. L. Mortensen.

inspection and maintenance or for replacement with a spare unit. Selector switches and relays of the type used in telephone exchanges have been adapted to this service, the entire interlock control operating from a 48-volt storage battery.

Elevator control has also been perfected to such an extent that uniform rates of acceleration up to speeds of 800 or 900 ft. per min. and correspondingly comfortable

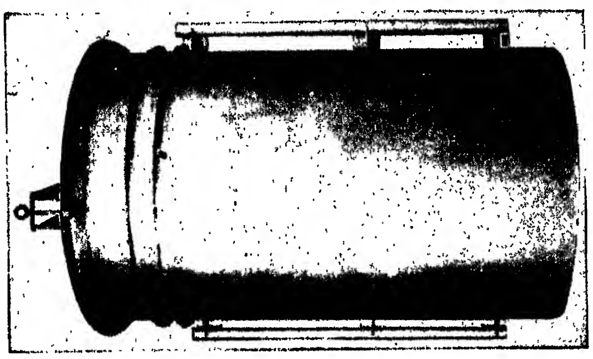

FIG. 19—THE TOP OF THIS FURNACE CAN BE READILY MOVED FROM BASE TO BASE

retardation to standstill at a predetermined floor level, may be made automatically with entirely enclosed passenger elevator cars. It is claimed that the high speeds are not objectionable to passengers if the walls of the shaft cannot be seen and if the acceleration and retardation are uniform.

Elevator control switches operated under the advantages of direct current are now possible from an a-c. supply by the introduction of a recently developed copper-oxide rectifier unit. This adaptation should prove popular because of its low space factor, low cost and sturdy construction. Similarly, the d-c. brake can

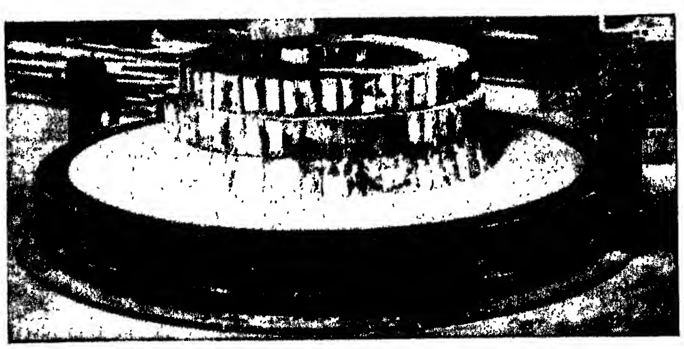

FIG. 20—THE BASE OF THIS FURNACE REMAINS FIXED, THE REMOVABLE HOOD FITTING DOWN OVER THE CHARGE

be used with a-c. drive of hoisting machinery with the intermediate rectifier unit.

Another interesting application of the copper-oxide rectifier was made to the control of polarity in building up the voltage on synchronous converters. A double-wave rectifier supplied a separate source of direct current. A blocking rectifier in the converter field circuit makes it possible properly to bias the excitation during the starting period by utilizing the positive half of the wave and stopping the negative half. The double-wave rectifier is connected in parallel with the converter armature so that it is only necessary to open the separate source of excitation and short circuit the blocking rectifier when synchronous speed is reached. No transfer equipment is, therefore, necessary. In some of the smaller installations even the brush raising mechanism has been eliminated.

The "fuseless fuse box," or small circuit breaker for domestic appliance and panel-board use, to take the place of fuses, is as simple as a light switch, cannot be "held in" upon injurious overloads, is safe, moisture and shock proof, and should meet with generous usage in the multi-motored home, office, and factory.

The deion principle, which was first applied to relatively high-voltage, heavy-current circuit breakers, is now available for industrial control breakers in 440- to 600-volt motor circuits, thereby providing greater

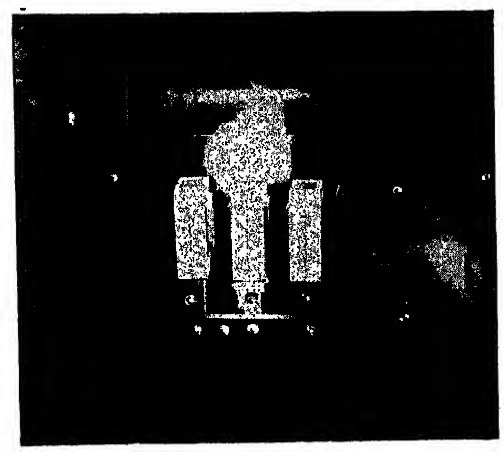

FIG. 21—ORDINARY ARC CHUTE ON A SWITCH

interrupting capacity in small enclosures. The application of this principle produces rapid deionization of the arc path after the factors producing ionization have become inactive at the cyclic zero of the current wave. The magnetic blow-out coil is thus eliminated. A comparison between the flame emitted from an ordinary breaker and a deion breaker when opening the same load is shown in Figs. 21 and 22. Tests have been reported upon a deion contactor rated for a 40 hp., 440-600-volt circuit in which currents as high as 2500-amperes were successfully interrupted at 48 per cent power factor.

A unique oil type hydraulic operating unit to take the place of large a-c. or d-c. magnets and solenoids, or even air cylinders, where quiet and smooth mechanical thrust is desired throughout a definite distance, consists of a motor-driven oil centrifugal impeller pump located within the movable piston itself. The moving impeller is driven from a stationary motor by means of a spline shaft. In the normal position the piston is at the bottom of the cylinder, which is approximately two-

thirds full of oil. When energized, the motor drives the impeller, thereby creating a pressure between the bottom of the piston and the bottom of the cylinder. This pressure tends to move the piston upward throughout the full length of the cylinder.

Metal-clad switchgear continues to merit further application and successful operation, although its details are far from standardized as yet. Fillers of hard asphaltum compound, petrolatum or vaseline and thin insulating oil, each with its advantages for certain classes of service, are being thoroughly tried out. Care should be exercised in defining and developing standards to distinguish between metal-clad switchgear, with its complete insulation of all parts and resultant space reduction, and the contrasting conventional truck type switchgear.

In connection with motor operation of large valves in steam power plants and in the chemical industry, the

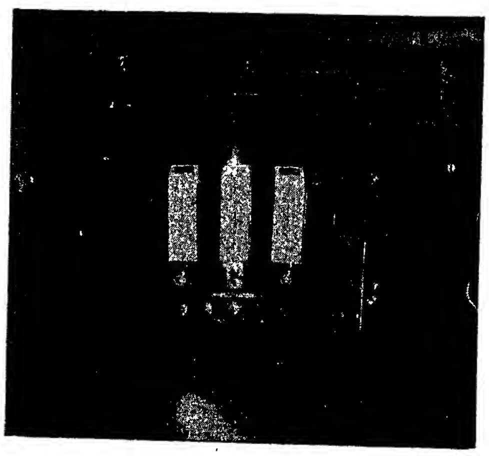

Fig. 22—Arc on Deion Switch When Opening Same Load as Switch in Fig. 21

trend toward extremely high pressures, up to 3000 lb. per sq. in., and relatively high temperatures, has imposed unusual requirements as to positive and accurate seating of the valves. Strains and resultant deformation may result from the pressures and from expansion and contraction of parts due to temperature changes. Also dissimilar metals are used, such as monel stems and chrome steel valve bodies which have unlike temperature coefficients of expansion. Therefore, the standard motor control with a mechanical limit set for an accurate number of turns of the yoke nut would not, under certain conditions, close the valve tight, while under other conditions it might seat the valve before this mechanical limit was reached and thus damage the valve seat.

A torque limit device known as a "valve-tight-seating relay" was developed to meet these varying conditions. This relay is used in connection with the valve control and assures a seating of a valve at a definite, predetermined seat pressure, or a fixed torque on the motor.

The "tight-seating relay" operates on the lock-out principle, or rather, the lock-in principle. The pivoted armature of the relay is held in by a calibrated spring and a shunt magnet. A series magnet on the opposite side of the pivot tends to pull the relay armature out. The pull of the shunt coil is in excess of that required to hold the relay in on the high current inrush of starting the motor. The mechanical limit of the valve operating mechanism is connected to the shunt coil. This limit is set to open the shunt coil while the valve is still an appreciable distance from the seat. As the valve approaches the seat, only the spring on the relay tends to hold the contacts closed. The valve seating pressure then builds up and increases the current passing through the motor and the series coil until this current reaches the predetermined value which then snaps the relay open and disconnects the driving latch, allowing the motor to drift on free of the valve mechanism.

This "tight-seating relay" system is unique in that the full torque of the motor is available clear up to the actual tight seated point on the valve. It also does away with the necessity of accurate setting of the mechanical limit.

A new design known as the duplex magnetic clutch has been developed. This type of clutch is for particular application to hard service.

In the duplex design the magnet members have no relative rotation. They are fastened together and rotate as a unit. The armature member is carried on a spring plate which is bolted at the inside to a projection from the field member. The magnet members carry flanges extending outward on which are mounted the metal friction members which clamp the lining faces. Provision is made for adjusting the distance between the metal friction faces and also for setting the lining carrier to provide positive clearance when the clutch is disengaged.

This design increases the lining area and the driving force for a given diameter, and reduces the possible damage which may result from improper maintenance. When the magnet members make contact as the lining wears, the clutch loses all driving force and obliges the maintenance crew to readjust. In that condition, the magnet members cannot score each other since they have no relative rotation.

Several devices for the control of motors are worthy of note. Fig. 23 illustrates a field relay for synchronous motors with definite time element and lockout coil. The lockout coil prevents the timing mechanism from operating until the motor has accelerated to approximately 95 per cent of synchronous speed when the voltage decreases, permitting the lockout coil to release the timing mechanism.

A new line of starters was developed for ¾-to 3-hp. d-c. motors. This definite-time starter, Fig. 24, is smaller and more compact than previous designs, although the three points of acceleration is an increase.

Definite time acceleration is adjustable over a range of from two to eight seconds.

TEXTILE INDUSTRY[9]

During 1929 there were at least two outstanding developments in applying electrical equipment to textile machinery.

The more important development was the application

FIG. 23—FIELD RELAY FOR SYNCHRONOUS MOTOR WITH DEFINITE-TIME ELEMENT AND LOCKOUT COIL

of a-c. variable speed motors to spinning machines, printing and finishing machinery, and full-fashioned hosiery knitting machines. Until recently this type of equipment has been driven with various degrees of success by d-c. adjustable-speed motors, by wound rotor-induction motors, multi-speed squirrel-cage motor or constant-single speed squirrel-cage motors with

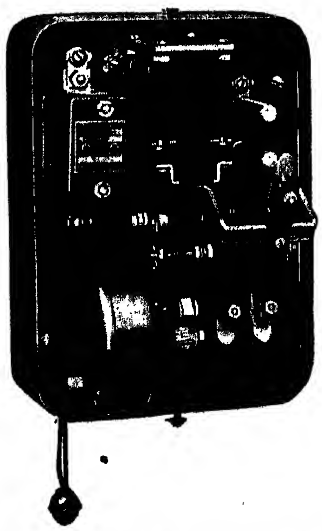

FIG. 24—DEFINITE-TIME AUTOMATIC STARTER FOR D-C. MOTORS

mechanical speed changing devices. With each of these drives there has been one or more undesirable features such as insufficient number of speed points, low efficiency, and inability to obtain exactly the same speed curve repeatedly without resetting the control.

Numerous applications of the a-c. adjustable-speed shunt-characteristic induction motor, Fig. 25, has demonstrated that this motor overcomes all of these disadvantages of the previous drives and permits easy but complete control of the process with improved quality and increased production. The successful and increasing use of this adjustable speed alternating current motor represents a distinct advance in the art.

Another definite development or trend has been the increasing use of "built-in" motors and individual drive with more compact control equipment, many tending toward simplification of the complete equipment and a reduction in the amount of floor space required.

The rayon spindle motor offers a notable example of the increasing use of individual drive. The trend for rayon motors has been toward higher speeds, such as

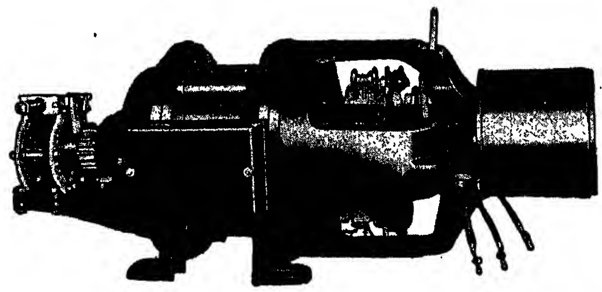

FIG. 25—3-HP. BRUSH-SHIFTING, ADJUSTABLE-SPEED, A-C. MOTOR

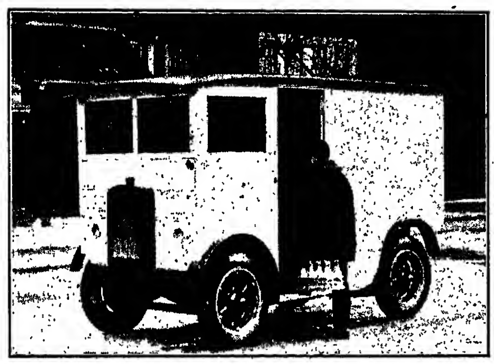

FIG. 26—GAS—ELECTRIC DELIVERY TRUCK IN DOOR-TO-DOOR SERVICE

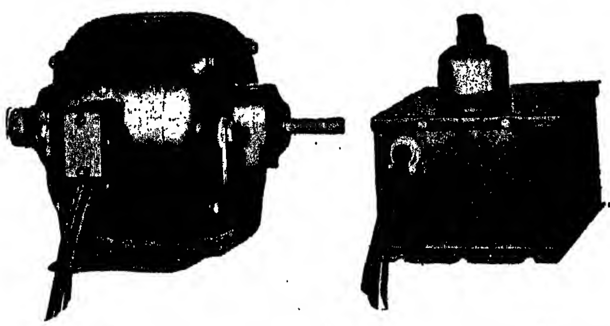

FIG. 27—1/4-HP. CAPACITOR MOTOR WITH THREE SPEEDS

8000 rev. per min. and upwards. While successful motors have been developed for even higher speeds than these, limitations in the strength of the buckets and in the process itself have somewhat retarded this trend. However, these difficulties are gradually being overcome.

The flexibility of individual drives, together with the improved quality of product, as demonstrated in rayon spinning, has caused a movement toward the use of individual spindle motors for silk and cotton machinery.

9. Contributed by C. W. Falls.

This trend will be watched with great interest by the textile industry.

During 1929, motors were built more compactly into looms and similar machines, with resulting simplicity and economy in floor space. There seems to be considerable opportunity for development in this direction.

Coincident with this movement has been the introduction of very compact combination controllers, which reduce the required space and wiring to a minimum. These control devices combine in one case the motor starter, full protective features, safety disconnecting means and fuses for short-circuit protection.

FIG. 28—THE ABOVE MOTOR DEVELOPS 1250 HP. AT 3600 REV. PER MIN. TO THE RIGHT IS THE ROTOR OF ONE OF THESE MOTORS

MISCELLANEOUS APPLICATIONS

Telephones. The continued and rapid increase in the use of the dial system means, of course, a continually increasing power demand for telephone central offices. In the larger cities the panel system is being employed which uses motors for driving the switches rather than magnets. The telephone central office is thus more and more becoming a user of power of some magnitude, and a larger field of power applications is steadily being opened.

Gas-Electric Busses. Over two hundred busses with gas electric drive were put in service during the year. The general trend in busses is toward larger size, which greatly favors gasoline-electric drive as it is superior to mechanical drive in large units.

Development of a pleasure car with this type drive was undertaken during the year. Five cars were so equipped and tests indicate that the smooth acceleration and easy handling obtained with electric drive will make this application a commercial success when equipment is fully developed.

Gasoline-electric drive has already been applied to small delivery trucks for door-to-door service. Fig. 26 shows one of the 100 Thorne delivery trucks put in service during the past year.

An unusual application of this drive was made by the U. S. Signal Corps. Three 1½-ton trucks with paneled bodies were equipped with motor-generator sets and switchboards. Two of the trucks supply current at 2000 volts to the radio transmitter and the other supplies 12-volt current for battery charging.

Capacitor Motors. Although the operation of repulsion motor has been satisfactory on fans, blowers and unit heaters, the need of an even more quiet motor which would not cause radio interference was apparent. Accordingly, the adjustable varying speed capacitor motor was developed for smaller ratings see Fig. 27. The capacitor is so connected in series with one phase of the two-phase stator that it will transform some of the input to make the motor operate like a polyphase induction motor. The other phase of the stator is connected to the speed adjustment switch which has four positions; high, medium, low and off. This causes the motor to operate at 90, 75, and 65 per cent of synchronous speed when loaded to rated capacity.

High-Speed Motors. In order to raise the feedwater to a pressure of nearly 1600 lb. in the Deepwater station, New Jersey, eight 1250-hp. induction motors driving five stage centrifugal pumps were installed. These motors develop a speed of 3600 rev. per min., the limit for 60-cycle motors. A feature of the motors is the size of the rotors which have a diameter of about 15 in., which compares favorably with the size of the rotor in a 900-rev. per min., 100-hp. motor. Fig. 28 illustrates these motors.

The committee is indebted to the following firms, institutions and publications with which committeemen are connected or whose cooperation and publications we have made use of in compiling this report:

American Brown Boveri Company.
Bethlehem Steel Company.
Bell Telephone Laboratories.
Braymer Equipment Company.
Cutler Hammer Manufacturing Company.
Duquesne Light Company.
Electric Power Equipment Company.
General Electric Company.
Lehigh Portland Cement Company.
Massachusetts Institute of Technology.
National Council of American Shipbuilders.
Philadelphia Electric Company.
Purdue University.
Reliance Electric & Engineering Company.
University of Toronto.
Westinghouse Electric & Manufacturing Company.
J. G. White Engineering Corporation.
Iron and Steel Engineer Magazine.
Electrical World Magazine.
Machine Design Magazine.

Instruments and Measurements

ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

To the Board of Directors:

The Committee on Instruments and Measurements reports activities for the past year as follows:

1. Measurement of Core Losses in Terms of Sine-Wave Core Losses.
2. Method of Measuring Distortion Factor.
3. Dielectric Power Loss and Power Factor Measurements.
4. High-Frequency Measurements.
5. Definitions Relating to Telemetering.
6. Measurement of Starting Currents in Fractional Horse-power Motors.
7. Standard for Recording Instruments.
8. Revision of Standard No. 14, Instrument Transformers.
9. Convention of Phase Angle in Instrument Potential Transformers.
10. Standard on the Technique of Temperature Measurement.
11. Reactive Power.
12. Papers.
13. Conclusion.

Measurement of Core Losses in Terms of Sine-Wave Core Losses

Last year, the Committee outlined three suitable methods for correcting results of core loss measurement to a sine-wave basis when made with a distorted wave of applied voltage, and for such correction recommended preference for methods utilizing average voltage. (See Annual Report, Committee on Instruments and Measurements, A. I. E. E. Trans., Vol. 48, Oct. 1929, p. 1386).

Following this recommended preference, the Committee has recommended that a method based on the measurement of average voltage be used for correcting core loss results to a sine-wave basis when made with a distorted wave of applied voltage. This action has been regularly transmitted to the transformer subcommittee of the Committee on Electrical Machinery, and to the Standards Committee.

Method of Measuring Distortion Factor

Last year the Committee defined "distortion factor" of a voltage wave and suggested several methods of measurement. Of these, the use of the Belfils Bridge seemed to be the most promising, though it was recognized that further study and development of the apparatus was necessary. (See Annual Report, Committee on Instruments and Measurements, A. I. E. E. Quarterly Trans., Oct. 1929, Vol. 48, p. 1386.)

This year, the Committee reports that a Belfils Bridge has been built and is being used for further study of distortion factor in electrical rotating machinery.

A "dynamometer method" for measuring distortion factor has been suggested, but upon investigation it was found that this method belonged in previous Classification D covering "harmonic analyzers."

Dielectric Power Loss and Power Factor Measurements

During the past year, there has been relatively little advance made in the development of new apparatus or new methods for the determination of dielectric loss and power factor. The various people interested in these measurements have concentrated on making their apparatus more workable, the changes made in technique and apparatus being of a very minor nature.

One interesting application is that of the phase defect compensation method to the three-phase measurement of dielectric power loss and power factor.

Work is being continued on the development of high-capacitance standards for use in checking equipments designed for measurement on full reels of cable. Work on these standards is under way at the present time and it is hoped to develop a capacitor having a capacitance of 0.1 μf. for use on voltages as high as 45 kv. It is hoped that the capacitor will have a power factor of approximately 0.0025, and will be unaffected by temperature or other operating conditions.

High-Frequency Measurements

The subcommittee has prepared a partial list of measurement papers appearing in 1929. This is given in Appendix A of this report.

Definitions Relating to Telemetering

The subcommittee on remote metering has prepared definitions of terms relating to telemetering which by Committee action are given here for comments, which are solicited and should be sent to the secretary of the committee, H. C. Koenig:

Telemeter: Measuring, transmitting and receiving apparatus for indicating, recording or integrating at a distance by electrical means the value of a quantity.

Telemetering: The indicating, recording or integrating of a quantity at a distance by electrical translating means.

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*COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:
Everett S. Lee, Chairman,
H. C. Koenig, Secretary,
E. J. Rutan, Vice-Chairman,

O. J. Bliss,	M. Eastham,	W. B. Kouwenhoven,
Perry A. Borden,	W. N. Goodwin,	F. A. Laws,
W. M. Bradshaw,	F. C. Holtz,	R. T. Pierce,
H. B. Brooks,	J. A. Johnson,	G. A. Sawin,
A. L. Cook,	I. F. Kinnard,	R. W. Sorensen,
E. D. Doyle,	A. E. Knowlton,	H. M. Turner.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

Voltage (Type) Telemeter: A telemeter which depends on the variation of a voltage as the translating means.

Current (Type) Telemeter: A telemeter which depends on the variation of a current as the translating means.

Frequency (Type) Telemeter: A telemeter which depends on the variation of a frequency as the translating means.

Impulse (Type) Telemeter: A telemeter which depends on electrical impulses as the translating means.

Duplicate Position (Type) Telemeter: A telemeter which depends on duplicating at the receiving end changes in angular relation or impedance of the translating means.

Direct-Acting (Type) Telemeter: A telemeter in which the translating means (voltage, current, frequency, etc.) increases in value with increase in the measured quantity.

Inverse-Acting (Type) Telemeter: A telemeter in which the translating means (voltage, current, frequency, etc.) decreases in value with increase in the measured quantity.

Note: In the above definitions the word "type" has been included in order to make clear the characteristic being defined. It is hoped that, after these definitions have more common application, the word "type" may be dropped and the terms used understood.

It is suggested that a telemeter which measures
Current be called a teleammeter.
Voltage be called a televoltmeter.
Watts be called a telewattmeter.

Measurement of Starting Currents in Fractional Horsepower Motors

A subcommittee has prepared the following report relative to measurement of starting currents in fractional horsepower motors.

"In 1925 one of the large middle western power companies undertook an independent investigation into the operating characteristics of fractional-horsepower motors. This investigation was started because of the numerous service calls due to flicker in lamps caused by the starting of small motors operated from the same lighting circuit.

"A paper on this subject was read at the 1925 annual meeting of the Association of Edison Illuminating Companies. Shortly thereafter a joint committee was formed which included representatives from the Association of Edison Illuminating Companies, National Electric Light Association, National Electrical Manufacturer's Association, the American Washing Machine Manufacturers' Association and various individual manufacturers of small motors and of motor-driven domestic electrical equipment. This committee held several meetings in 1927, 1928 and 1929, resulting in the setting up of specifications for performance of fractional-horsepower motors. These specifications are in use and are readily applied in all particulars except the limitation upon starting current.

"In the specifications of the joint committee and also in other specifications issued by various engineering societies, starting current has been defined as the reading obtained on a well-damped ammeter. Efforts to determine compliance with the specifications of the joint committee brought about discussions as to the methods of measuring such starting currents. It was suggested at the meeting of the Instruments and Measurements Committee held on November 29, 1929, that the question of measuring starting currents could very well be considered by a subcommittee. A subcommittee was appointed to investigate the question, and report to the main committee.

"The starting current taken by a fractional-horsepower, single-phase motor persists for a relatively small number of cycles.

"In the case of repulsion-induction motors, the maximum current drawn in the first cycle falls rapidly in successive cycles, is suddenly increased momentarily by the action of the short-circuiting device on the rotor, and then quickly reduces to the normal running current.

"In the case of split-phase motors, the initial input may persist for from 6 to 15 or 20 cycles, and is then rapidly reduced to the normal running current.

"The ideal instrument for the measurement of starting currents would, of course, be the oscillograph. There is no question that the oscillograph represents the true conditions in the motor circuit during the starting period. Because of its expense and bulkiness, however, the oscillograph does not readily lend itself to the measurements of starting currents in the field.

"On the other hand, readings of an ammeter must be interpreted in terms of damping and inertia of moving parts, personal equations, and the magnitude and duration of the starting current as actually recorded by the oscillograph.

"In other words, we have at least five variables to be considered in setting up any standard method for measurement of starting currents for small motors.

1. Meter damping.
2. Inertia of moving elements of meter.
3. Initial amplitude of starting current.
4. Duration of starting currents.
5. Personal equation.

"The nearest approach to the oscillograph in an a-c. instrument would be one which is critically damped and has such a short period (by reducing the moment of inertia or increasing the restoring torque) that its pointer would follow exactly the changes current. Such an instrument must have a period of the order of 0.01 second or less, which naturally places it outside the class of ordinary a-c. ammeters.

"The action of a current of short duration on the ordinary a-c. instrument has a ballistic effect, but unfortunately this effect is not proportional to the current or its square, but depends upon $\int i^2\,d\,t$, which shows

that the same indication would result for widely differing currents provided they had correspondingly different durations. This effect is further complicated by the fact that the electromagnetic constant of the instrument varies greatly throughout its scale, so that the ballistic effect depends in addition upon the duration of the current relative to the responsiveness of the movable system, which differs among instruments of various manufacturers and even among instruments of the same manufacturer.

"It seems evident therefore that the simple indication of any of the ordinary a-c. ammeters cannot be used as a measure of current for short durations, such as motor starting currents.

"Since the origin of this investigation was concerned with the flicker effect upon lamps, it seemed logical to study motor starting currents in relations to the physiological perception of flicker. Recent studies have tended to show that the physiological effect of flicker produced in the starting of motors was approximately proportional to the locked-shaft current.

"In view of the above facts the committee recommends the use of an ammeter equipped with an adjustable backstop, by means of which the pointer can be initially set at any place upon the scale. By making several trials, a point can be found from which the pointer moves but very slightly upon the starting of the motor. This point has been found to be the maximum current drawn by the motor in starting. In other words, it is approximately equivalent to the locked-shaft current. This meter therefore, permits the measurement of locked-shaft current without the attendant difficulties due to heating.

"The committee has not attempted to devise a new instrument for the purpose of measuring starting currents, for the instrument referred to has already been used for this and other work and can be made by any of the instrument manufacturers."

Standard for Recording Instruments

A tentative draft of Standard for Recording Instruments has been prepared, using Instrument Standards No. 33 as a basis and making necessary modifications and additions. The latest copy of this tenative draft is now being circulated to members of the subcommittee on recording instruments, and to other instrument manufacturers who are not represented on the Committee.

Revision of Standard No. 14—Instrument Transformers

A subcommittee has been appointed to revise Standard No. 14. Mr. E. J. Rutan is Chairman of this subcommittee.

Convention of Phase Angle in Instrument Potential Transformers

Present A. I. E. E. Standard No. 14, Par. 59 provides that for instrument potential transformers, the phase angle is conveniently considered as negative when the reversed secondary voltage vector leads the primary voltage vector. This convention, however, has not been universally followed. To harmonize procedure, the Committee has recommended to the Standards Committee that the rule be changed to provide that the phase angle be considered as positive when the reversed secondary voltage vector leads the primary voltage vector.

Standard on the Technique of Temperature Measurements

The Committee hopes to complete the work on this Standard during the coming year.

Reactive Power

The Committee is studying the question of the measurement of reactive power.

Papers

A total of twelve papers was reviewed during the year, eight of which were presented, as follows:

Measurement of Electrical Machine Characteristics

A Recording Torque Indicator that Automatically Records the Torsional Effect of Motors during Acceleration, G. R. Anderson, A. I. E. E. Quarterly TRANS., Vol. 49, p. 333, January 1930.

Determination of Generator Speed and Retardation during Loss Measurements, O. E. Charlton and W. D. Ketchum, Northeastern District Meeting, Springfield, Mass., May 1930.

Measurement of Temperature

A Self-Compensating Temperature Indicator, I. F. Kinnard and H. T. Faus, A. I. E. E. JOURNAL, Vol. 49, p. 343, May 1930.

Measurement of Light

An Ultra Violet Light Meter, Dr. H. C. Rentschler, A. I. E. E. Quarterly TRANS., Vol. 49, p. 546, April 1930.

Oscillographs

Design and Application of a Cathode Ray Oscillograph with Norinder Relay, O. Ackermann, A. I. E. E. JOURNAL, Vol. 49, p. 285, April 1930.

A New Portable Oscillograph, C. M. Hathaway, North Eastern District Meeting, Springfield, Mass., May 1930.

Network Analyzer

The M. I. T. Network Analyzer, H. L. Hazen, O. R. Schurig, M. F. Gardner, North Eastern District Meeting, Springfield, Mass., May 1930.

Air Capacitors

Phase Difference in an Air Capacitor, W. B. Kouwenhoven and C. L. Lemmon, North Eastern District Meeting, Springfield, Mass., May 1930.

Conclusion

The interest of the members of the Committee on Instruments and Measurements has been maintained in its activities during the past year, resulting in definite action on several subjects. The study now being given to present projects should result in further definite action next year.

APPENDIX A

A partial list of papers on high-frequency measurements appearing in 1929.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS QUARTERLY TRANSACTIONS, APRIL 1929, VOL. 48

Ionization Studies in Paper-Insulated Cables, C. L. Dawes, H. H. Reichard, P. H. Humphries, p. 382.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS QUARTERLY TRANSACTIONS, JULY 1929, VOL. 48

Electrical Instruments Used in the Measurement of Flow, W. H. Pratt, p. 737.

Telemetering, Linder, Stewart, Rex and Fitzgerald, p. 766.

A Precision Regulator for Alternating Voltage, Stoller and Power, p. 808.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS QUARTERLY TRANSACTIONS, OCTOBER 1929, VOL. 48

Shielding and Guarding in Electrical Apparatus Used in Measurements—General Principles, H. L. Curtis, p. 1263.

Some Problems in Dielectric Loss Measurements, C. L. Dawes, P. L. Hoover, and R. H. Reichard, p. 1271.

Shielding in High-Frequency Measurements, J. G. Ferguson, p. 1286.

Guarding and Shielding for Dielectric Loss; Measurements on Short Lengths of High-Tension Power Cable, E. H. Salter, p. 1294.

Precautions Against Stray Magnetic Fields in Measurements with Large Alternating Currents, F. B. Silsbee, p. 1301.

Magnetic Shielding (Shielding of Magnetic Instruments from Steady Stray Fields), S. L. Gokhale, p. 1307.

Electrical Wave Analyzers for Power and Telephone Systems, McCurdy and Blythe, p. 1167.

Report of Committee on Instruments and Measurements, p. 1385.

Institute of Radio Engineers Proceedings, Vol. 17, 1929

"A Direct Reading R. F. Meter," R. E. Hitchcock, Jan., p. 24.

"An Extension of Method of Measuring L. & C., Harris, March, p. 516.

"Use of Electron-Tube Peak Voltmeter for the Measurement of Modulation," Joliffe, April, p. 660.

"Measurement of Height of Heaviside Layer," Kenrick and Jen, April, p. 711.

"Measurement of the Frequencies of Distant Radio Transmitting Stations," Pession and Gorio, April, p. 734.

"A Direct Reading Frequency Bridge Based on Hay's Bridge Circuit," Loury and Bayly, May, p. 834.

"Vacuum Tube Voltmeter Design," May, p. 864.

"Measurement of Direct Interelectrode Capacitance of Vacuum Tubes," Loughren and Parker, June, p. 957.

"Measurement of Directional Distribution of Static," Harper, July, p. 1214.

"Routine Measurement of Frequency of Broadcasting Stations," Bogardus and Manning, July, p. 1225.

"Electromagnetic Monochoid for Measurement of A. F.," Harries, Aug., p. 1316.

"Static and Motional Impedance of Magnetostriction Resonator," Lange and Myers, Oct., p. 1687.

"Inductance as Affected by Initial Magnetic State, Air Gap, and Superposed Current," Turner, Oct., p. 1822.

"Measurement of Frequency," Jimbo, Nov., p. 2011.

"Frequency Measurements Based on a Single Frequency," Hall, Feb., p. 273.

Bell System Technical Journal, Vol. VIII, 1929

"Articulation Testing Methods," H. Fletcher and J. C. Stemberg, p. 806.

"Braun Tube Hysteresigraph," J. B. Johnston, p. 286.

"High Precision Standard of Frequency," Marrison, p. 493.

"Shielding in High Frequency Measurements," Ferguson, p. 560.

"Observations on Modes of Vibration and Temperature Coefficients of Quartz Crystal Plates," Lack, p. 515.

"Loud Speaker Measurements," Bostwick, p. 135.

"Speech Power and Its Measurement," Sivian, p. 646.

"Physical Properties and Methods of Test of Some Sheet Non-Ferrous Metals," Townsend and Straw, p. 749.

"Test for Polarization of Electron Waves by Reflection," Davisson and Gerner, p. 466.

Journal of the Franklin Institute, Vol. 207, 1929

"Measurement of Sound Absorption Coefficients," Sabine, p. 341.

"A Mechanical Method of Measuring Sound Pressure," Eisenhour and Tyzzer, Vol. 208, p. 397.

Physical Review, Vol. 34, 1929

"Determination of Charge of Positive Irons from Measurements of Shot Effect," Williams and Huxford, Vol. 33, p. 773.

"Contact Potential Measurement with Absorbed Films," Langmuir and Kingdon, p. 129.

"Measurement of Ionization Potential in Mercury Vapor," Bleackney, p. 157.

"New Method of Measuring Dielectric Constant of Conducting Liquids," Aston, p. 300.

"Measurement of Discontinuous Change in Magnetization," Bozorth, p. 772.

"Dielectric Loss at High Frequency," Owen, p. 1035.

"Static Balance Electrometer for Measuring Dielectric Constants of Electroytes," Carman, Young and Smith, p. 1040.

"Variation of Dielectric Constant with Frequency," Johnston and Williams, p. 1483.

Institution of Electrical Engineers, Vol. 67, 1929

"Contact Effects Between Electrodes and Dielectrics," (E. R. A. Report).

"Precautions in the Use of Standard Instruments," Lawes, p. 541.

"Effect of Added Impurities on the Breakdown Voltage of Insulating Oils," (E. R. A. Report), p. 750.

"Recent Developments in Electricity Meters," Carr, p. 859.

"Electromagnetic Testing for Mechanical Flaws on Steel Wire Ropes," Wall, p. 899.

"Portable Radio Intensity Measuring Apparatus," Hollingworth and Marsmith, p. 1033.

"A Measurement of the Sound Pressure on an Obstacle," West, p. 1137.

"A Precise Electrometer Method for Voltage Transformer Testing," Spisbury, p. 1143.

"The Testing of Porcelain Insulators," Goodlit, p. 1177.

"Directions for the Study of Mecamte," (E. R. A. Report), p. 1243.

"Precision Permeability Measurements on Straight Bars and Strips in the Region of High Permeability," Webb and Ford, p. 1302.

Experimental Wireless and the Wireless Engineer, Vol. VI, 1929

"Notes on the Calibration, Permanence and Overall Accuracy of Series-Gap Precision Variable Air Condensers," Griffiths, p. 23, p. 77.

"Measurement of Grid-Anode Capacity of Tetrodes," Bligh, p. 299.

"The Problem of Grid Turn-Over Capacity," Reed, p. 310.

"A Portable Radio Intensity Measuring Apparatus for High Frequency," p. 316.

"Measurement of Wave Length of Broadcasting Stations," Braillard and Divoire, p. 412.

"Frequency Departure of Thermionic Oscillators from the LC Value," Pack, p. 472.

"Potential Difference and E. M. F.," Brederman, p. 481.

"Potential Difference and E. M. F.," (Comment on), Wilmotte, p. 551.

"Notes on Standard Inductances for Wavemeters and other R. F. Purposes," Griffiths, p. 543.

"Comparison of Power Factors of Condensers," Wilmotte, p. 656.

"A Sensitive Valve Voltmeter Without 'Backing Off'," Von Ardenne, p. 669.

Revue General de L'Electricite, Vol. 25, 1929

"Measurement of 'Residual' Voltage by Resonant Bridge," Belfils, p. 523, (Previous articles on same subject), Vol. 17, p. 32 and Vol. 18, p. 844.

"The Measurement of High Frequency by Means of Piezo-Electric Oscillators," Decaux, p. 322.

"The Calibration of Tuning Forks Used to Measure High Frequency," Decaux, p. 283.

"Contribution to Mathematical Theory of the Measurement of Inductance," Cobras, Vol. 26, pp. 939.

"Measurement of Very High Potentials by Means of a Spark-Gap in Air," A. Segall, Vol. 26, 1929, p. 716.

"Note on Measurement of Capacity Unbalance in Telephone Cables," Dimand, Vol. 26, p. 105.

Miscellaneous

"An Ampere-meter for Measuring Currents of Very High Frequency," Moullin, *Proc. Roy. Soc.*, Nov. 1928, p. 41.

"A Sensitive V. T. Voltmeter (Heterodyne)," *J. O. S. A.*, Dec. 1928, p. 440.

"Note on the Application of the Whiddington Ultra Micrometer," J. S. I., (London), March 1929, p. 81.

"Measurement of R. and L. of Iron Cored Coils Carrying Direct Current," Hartshorn, *J. S. I.* (London), April 1929, p. 113.

"A Method of Determining the Equivalent Resistance of Air Condensers at High Frequencies," Sutton, *Proc. Roy. Soc.*, Feb. 15, 1929, p. 126.

"A. V. T. Impedance Bridge," Stone, *J. O. S. A.*, Nov. 1929, p. 326.

"Characteristics of Audio-Frequency Transformers," Turner, *Proc.* Radio Club of America, Sept. 1929.

"Characteristics of Audio-Frequency Transformers," Turner, *Radio Broadcast*, Nov. 1929.

"On the Modes of Vibration of a Quartz Crystal," Harding and White, *Phil. Magazine*, London, Aug. 1929.

Applications to Iron and Steel Production

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION*

To the Board of Directors:

The unprecedented activity in the iron and steel industry, which resulted in record production of steel during 1929, is also indicated by the number of rolling mill electric drives purchased and installed.

Last year it was pointed out that synchronous motors for driving constant speed mills were increasing in number every year and this has been especially noticeable during the past year. Synchronous motors are desirable in any kind of constant speed mill application where the peak load conditions are not of sufficient size to interfere with the capacity of the power plant. One of the largest single installations of synchronous motors so far is that at the national works of the National Tube Company at McKeesport, Pa., where six large synchronous motors will be used for driving two seamless tube mills.

Hand-to-mouth buying by users of rolled steel products is one of the factors responsible for single mills being required to roll during one day small tonnages of a considerable variety of products. To meet this condition, the mills must be extremely flexible and this flexibility is most readily obtained by using individual adjustable-speed motor drive for all or many of the roll stands. An interesting example of this is a 15-stand, 10-inch merchant mill at the Indiana Harbor Plant of the Inland Steel Company which will be driven by 13 adjustable-speed d-c. motors, totaling 4900 hp.

The past year saw the application of the first twin motor drive to a blooming mill. The development of this idea has been carried on for some time and was probably an outgrowth of the idea of the individual stand drive which has been carried on for the past several years, on various types of billet, strip and skelp mills. The advantage of this type of drive is readily appreciated inasmuch as it eliminates the pinion stand with its losses and maintenance and at the same time permits a variation in roll diameter thus eliminating matching of rolls and permitting flexibility in the mill operation.

There is a continual demand from the steel plant operators to reduce delays and maintenance costs, and great strides have been made in the application of magnetic control in various motor drives.

There has also been further development in the automatic screw-down, which the year 1929 saw applied to plate mills and structural mills.

Development in the application of voltage control has continued to show the following advantages: less maintenance, ease of operation, faster manipulation of the screw-down, and simplicity of control. All of these factors are of vital importance and result materially in improved efficiency and increased production of the mills.

The control for reversing mill motors has been improved. This improvement includes the advantages gained on voltage control as applied to screw-downs, and simplified voltage control of reversing mill drive by controlling the fields of individual exciters for the motor and generator fields of a reversing mill drive. This has greatly reduced the maintenance on the field control equipment for reversing mills and has permitted simpler and more sturdy apparatus for field control. It has practically eliminated the high inductive arc on the field control panel contactors when a mill motor is accelerated and decelerated.

During the past year the installation of photoelectric cells for use as flag switches has incresed. In addition, the successful operation of the photoelectric cell has created other uses, such as direct and recording temperature indicators to replace the present pyrometer counters for sheets, tubes, billets and ingots, fire prevention, etc. The field for this little device is spreading rapidly and the demand for photo-electric cells in the steel mills in the next few years will be greatly increased. The design of this apparatus lends itself to practically any application where it is desired to automatize a mechanical operation or adjust an operating condition to obtain increased production.

Extended research and experiment are being made in the economical use of fuel in steel mills. The electrically operated recording calorimeters and electrically operated gas meters are being used to control the combustion automatically and more economically.

The use of electric welding has developed enormously in the steel mills. Particularly of note is the development in the electric welding of steel tubes.

A new mill which eliminates all hand and mechanical puddling, has been completed at Pittsburg for the manufacture of wrought iron. This plant is electrically equipped throughout and is the most modern mill in the world electrically operated for the manufacture of wrought iron. The method of operation consists essentially of pouring molten iron over molten cinder in a ladle under suitable conditions to form a ball. This ball is then formed by a powerful motor driven

*COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION:

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A. C. Cummins,	F. O. Schnure,	T. S. Towle,
S. L. Henderson,	W. B. Shirk,	J. D. Wright.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

press into a bloom which in turn is rolled down in the electrically operated blooming mill to muck bar or billets preparatory to being sent to the skelp mills.

Up to this time the limiting feature in the wrought iron industry has been the economical inability to produce wrought iron on a quantity basis. As a result, the principal use of wrought iron has been confined to the manufacture of pipe. With the development of this new method of making wrought iron on an economical quantity basis there will undoubtedly be markets opened to it where previously it was unable to compete.

The growth of blast furnace production is being greatly assisted by the automatic operation of skip hoists, the application of stock line recorders, pyrometers and other features that tend to give the furnace operators more information regarding their operation.

Production and Application of Light

REPORT OF THE COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

To the Board of Directors:

Production of Light

Statistics on Incandescent Lamp Sales.[1] The sale of large tungsten filament lamps (as distinguished from the miniature types) totaled 344,000,000 during 1929, an increase of 8.7 per cent over the previous year's sales. The fact that the production of large tungsten filament lamps alone is running well over a million lamps per working day will give some impression of the extent to which our modern life has become dependent upon this source of artificial illumination.

For these lamps the average watts per lamp in 1929 ran 60.7 as compared with 51.5 in 1919, and the average lumens per watt were 13.1 as compared with 10.5 ten years previously.

In the 100-130-volt range half of the incandescent lamps sold (49.5 per cent) were of 115 volts, 39.4 per cent were of 120 volts, 6.5 per cent were of 110 volts, and 3.4 per cent were of 125 volts, these four voltages accounting for 98.8 per cent of the total. Lamps for 220-260 volt service totaled in quantity 3.3 per cent of that supplied for the lower standard voltage range. These facts should be of special interest to electrical engineers as indicative of the trend of voltage standardization.

The Service Voltage Standardization Committee of the Apparatus Committee of the National Electric Light Association recommended some years ago as standard practise the selection of such a service line voltage as will supply the proper average voltage to 115-volt lamps, with recognized departures in the case of 110-volt systems and existing 120-volt systems. As there is commonly at least two or three volts drop in the interior wiring the voltage delivered at the customers' service switch should be correspondingly higher in order to supply an average voltage at the socket corresponding to the standard voltage of lamp selected for use.

Sources of Ultra-Violet Radiation. Within the past year there has been a marked advance in the production and home use of ultra-violet for artificial sunshine. The American public has shown a great interest in this development.

In a paper, *Simulating Sunlight—A New Era of Artificial Lighting*, presented at the Winter Convention, Dr. M. Luckiesh described a new tungsten-mercury arc lamp made in a bulb of special glass which transmits the short wave radiation desired. This lamp has been developed to provide a simple source of artificial sunlight having the same general form as that of an incandescent lamp. The lamp operates on low voltage, and must be used with a transformer designed with a special shape of drooping characteristic curve. A tungsten filament is placed in parallel with the arc. The filament lights first, and almost instantly some of the mercury in a small globule free in the bulb becomes vaporized and the mercury arc is formed between the tungsten electrodes. The initial starting voltage applied to the filament then drops to the normal operating value.

The carbon arc lamp has during the past year been developed to a high degree of efficiency for the reproduction of sunlight in the home. The use of cerium-cored carbons, for example, with a carefully designed chromium-plated reflector, enables it to give a close reproduction of natural sunlight throughout the ultra-violet, visible and infra-red zones. Filters of special glass can be used to cut out the very short ultra-violet radiation and transmit only that part found in natural sunshine. A limited burning period provides an important safety feature.

Other Lamp Developments. The use of larger screens in the projection of motion pictures and the probability of the perfection, in the near future, of methods for stereoscopic projection, have created a demand for a source of light of greater brilliancy than any now in use. This demand has been met by the development of a super high-intensity projector carbon. Operated at a current of 225 to 250 amperes, this carbon arc possesses an intrinsic brilliancy 50 per cent greater than the sun at zenith.

The use of gaseous conductor lamps has continued to increase during the year, and developments in the field of the hot-cathode neon lamp and in a type of lamp which produces in a single tube a light which appears subjectively white are reported in progress.

Utilization of Light

Color Lighting. Important developments have been

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Mr. W. T. Blackwell,	Prof. H. H. Higbie,	Prof. W. T. Ryan,
Prof. J. M. Bryant,	Mr. W. C. Kalb,	Mr. B. E. Shackelford,
Mr. W. T. Dempsey,	Prof. C. L. Kinsloe,	Mr. C. J. Stahl,
Mr. E. E. Dorting,	Mr. R. D. Mailey,	Mr. G. H. Stickney.

1. The Lamp Committee of the National Electric Light Association presents each year to that association a report in which the statistics relating to incandescent lamp production are analyzed in detail, and in which important developments in the production and application of light are reviewed. It is impossible to deal with this subject without covering much of the same ground. However, the statistics presented and the features of the past year's progress commented upon in this report are believed to be of particular interest to the electrical engineering profession. Those who wish more detailed statistics, as well as those who are concerned with the commercial and engineering problems of lighting, will find valuable the reports of various committees of the National Electric Light Association and the Illuminating Engineering Society.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

made during the year with regard to the production of color-lighting effects in conjunction with which several systems for controlling the voltage of large blocks of power supplied to incandescent lamps have been employed. In this field the Selsyn-Thyratron Control system, used in the Chicago Opera House, and the system installed at the Barcelona Exposition (as described by Mr. C. J. Stahl in an Illumination Item in the A. I. E. E. JL., December, 1929, p. 918) may be mentioned particularly. A device known as the "Lumitone" has also been developed to provide for manual or automatic control of color lighting circuits. These systems of control have placed at the disposal of the illuminating engineers more efficient and effective tools with which to work and will help further to popularize color lighting.

In this connection a simple yet effective application of controlled color lighting has made its appearance in the form of the Colorama, first used in the Ballroom of the St. George Hotel in Brooklyn.[2] The room is finished in flat white, and the money that would otherwise have been spent for the usual sort of wall and ceiling decoration has been put into an elaborate system of concealed color lighting by which patterns of colored light in never-ending variety are thrown on walls and ceilings. Another form of interior color lighting has been used effectively in the Sherman Hotel, Chicago.

Modernistic Note in Lighting. Modernistic lighting, referred to in the report last year, has continued to grow rapidly in favor, particularly in lobbies, entrances for office buildings, and commercial establishments visited by the public. The movement is being reflected somewhat in residential lighting equipment.

Lighting for Aviation. This subject was dealt with at length in last year's report. The incandescent lamp is used extensively in this field where the ease with which it lends itself to remote control and to operation by inexperienced personnel are important factors. The number of lighted airports has jumped from about 75 to over 300 during 1929. There has been a considerable improvement in the design of field lighting equipment as well as an extension in the application of light in actual aerial navigation.

An important contribution to the solution of the problem of night illumination of airports has been made through the use of a carbon arc searchlight equipped with a lens throwing a flat beam of wide horizontal distribution. This "pancake" of light provides good ground illumination over a radius of more than 5000 ft. The point source of light permits the use of a shadow band or path, which can be controlled from the operating tower, to protect the eyes of the aviator from glare while landing.

A method of tapping high-tension transmission lines for small amounts of power has been developed which is of interest in marking them with light in the vicinity of air ways and airports. In this system, capacitors made up somewhat similar in form and appearance to ordinary type high-tension insulators, are used. A series of these capacitors, their number depending upon the voltage of the line, is supported from the tower and the terminal on the lowest capacitor is connected to the line, while the terminal at the top is connected in series with the lighting unit to ground.

Silent Carbon Arc. The perfection of a method for silencing the carbon arc by filtering out the commutator ripple has placed it in a position where it can be used in the production of sound motion pictures, from which field it had been temporarily barred. A high capacity electrolytic condenser is connected from a point between the auxiliary and series field windings to the opposite terminal of the d-c. generator. Oscillograph tests show that the commutator ripple and consequent arc noise are effectively eliminated by this means.

Other Applications. A possible application of underwater lighting, described in the annual report last year, may be found in outlining seaplane base landing areas with light. The lighting of football fields and race tracks is becoming increasingly popular and is now fairly well standardized, increasing the recreational opportunities afforded to the public. The popularity of such night sports is indicated by the increased attendance as compared with that at similar contests held during the day; night attendance has been reported to run from two to ten times the usual day figure. Baseball is now being added to the list of night-lighted sports.

PRESENT SATURATION IN LIGHTING

A subject of basic interest to the electrical industry was dealt with at a meeting of the New York Section of the A. I. E. E.[3] under the title of *How Much Light.* The results of a careful study made by an informal committee organized at the instance of the New York Section, "to set up an approximate estimate of the present percentage saturation of the United States in artificial light," were presented. It was estimated that the present annual consumption of 20 billion kw-hr. for lighting would have to be increased to approximately 151 billion to provide the level of illumination of probable greatest economic advantage. The present saturation in artificial light as compared with the desirable value, based solely on eye considerations, was estimated to be about 3 per cent. The room for growth in the field of electric lighting, in spite of all the progress that has been made in the last quarter century, is still very great. Physical limitations, particularly in the distribution of energy, must be removed or overcome

2. See "Decorating with Light," *The American Architect,* Feb. 1930, p. 26; "Decorative Color Lighting," by A. T. North, *Architectural Forum,* Feb. 1930, p. 288.

3. See A.I.E.E. JL., Vol. 49, January 1930, p. 70. The report was submitted to the meeting by Frank W. Smith, Chairman of the Lamp Committee of the N. E. L. A., Arthur E. Allen, Vice-President, Westinghouse Lamp Co. and Dr. E. E. Free, Consulting Engineer.

before the electric lighting field can develop as freely and rapidly as it should, and this is a problem of particular interest to the electrical engineer.

Operating Voltage in Relation to Lighting

Voltage Conditions on Lighting Circuits. The past year has seen a general and rather surprised awakening, on the part of the electrical industry engaged in furnishing electrical energy and equipment for lighting, to the fact that the ever-increasing demands for electric light and electric service have in many cases thrown such heavy loads on existing circuits that the voltage delivered at the point of utilization during the hours of greatest use is considerably below the presumed nominal value for which the devices have been designed to operate. When the voltage at the socket is less than this normal value the customer spends less for energy to operate the lamps and for lamp renewals, but he gets so much less light in return for his reduced expenditure that the unit cost is increased and, of course, the illumination he receives from each unit is also diminished, as one per cent reduction in voltage reduces the light output about 3.4 per cent.

The problem of delivering electrical energy at the proper voltage to the point of utilization is worthy of the electrical engineer's most careful study. He should first of all have a clear comprehension of the effect of voltage variations on the wattage consumption, light output, operating cost and unit cost of light production with incandescent lamps as this is essential to the proper treatment of the problem of the economic production of light. It is rather difficult to visualize the relations of the several elements involved in this problem, especially when the effect of wiring losses and fixed charges on the wiring are taken into account (as they should be). On this account an animated form of voltage demonstration chart has been devised as a means of presenting these data.

The subject has been discussed at length from the point of view of the central station in the 1930 report of the N. E. L. A. Lamp Committee, in which the results of an extended survey of socket voltages are given.

The Mean-Voltage Meter. A device for measuring average voltage, described in an Illumination Item in the A. I. E. E. Jl., May, 1929, p. 397, has been redesigned and is now produced in a more compact form. One element is virtually a watt-hour meter with two potential coils instead of a voltage and current coil so that it registers volts squared times hours in place of watt hours. The other element is a telechron which gives the time reading so that the average voltage (root mean square) can be easily obtained. It is designed for use on 60-cycle current, 100-130 volts. This device, plugged in at the lamp socket, records only when the lamp is in operation so that it shows the average voltage delivered to the lamp during the time it was in operation. It should find extensive use in making surveys for the purpose of correcting the undervoltage operation of lamps and other electrical devices. Where recording meters are used for obtaining average socket voltage they should also be plugged in at the lamp terminal so as to register only when the lamp is burning. Voltage at other time does not affect the lamp.

Interior Wiring

Installation Standards. The problem of maintaining the proper average voltage at the socket also involves the question of the voltage drop in the wiring on the customer's premises. In last year's report reference was made to the preparation of a set of model specification paragraphs dealing with the adequacy of wiring. The Commercial and Industrial Lighting Committee of the N. E. L. A., with the collaboration of other branches of the industry and with other authorities interested in this subject, has prepared and recently issued a minimum specification for the adequate wiring of lighting circuits in commercial and public structures. Every electrical engineer who is brought into contact with the design or operation of lighting installations should be familiar with these specifications.

In this connection the wiring of the Chrysler Building described in two articles, "Wiring the World's Tallest Building," by David M. Goe, and "Chrysler Building Feeder Design," by L. Mackler, both appearing in *Electrical Contracting,* March, 1930, is well worth careful study because it represents advanced practise and refinement in design. Primary current is carried at 13,800 volts to the basement, the 30th, 60th and 72nd floors where secondary switch boards are located. The first article considers the average individual occupant in relation to his electrical requirements, floor area basis for circuiting, flexibility, facts rather than assumptions, adequacy, standardized feeder lengths, and provisions for the future. The second article describes in detail the calculations and recheck made to insure adequacy and adherence to voltage drop requirements. All this is very important from the standpoint of the application of light for it is not uncommon to find lamps operating at a voltage five or more volts below their labeled values in commercial buildings and probably rather more than this in industrial plants (extreme cases running as low as 80 per cent have been found). This undervoltage burning diminishes the light output more than it does the operating cost and results in inefficient and unsatisfactory lighting service.

Miscellaneous

Photoelectric cells are finding use in conjunction with the control of lighting installations. Electric signs, ordinarily operated by time clock alone, can have the photoelectric cell control added so that the sign will be lighted during exceptionally dark periods of the day during which it would ordinarily be unlighted. Many other applications will in all probability be found as the equipment is further developed.

A new system of interchanging lighting information

among lighting engineers through the medium of data sheets describing outstanding installations has been inaugurated by the I. E. S. Committee on Lighting Service.

The accepted specifications for motor vehicle headlights have been revised by the I. E. S. Committee to include the dual-beam type of equipment, a revision of the tail-light specification is practically complete, and a new signal light specification has been drawn up.

The celebration in this country of Light's Golden Jubilee officially opened with elaborate lighting effects and special ceremonies, at the time of the National Electric Light Association Convention in Atlantic City last June. Wide-spread interest and enthusiasm lead up to the grand climax at Mr. Ford's dinner on October 21st, at which Mr. Edison completed a model of his early lamp in his old laboratory reconstructed by Mr. Ford at Dearborn.

The proceedings of the meeting of the International Commission on Illumination held in September, 1928, have been issued during the past year. The U. S. National Committee of the I. C. I. has been actively interested in the preparations which are being made for the meeting to be held next year in England. It has been especially concerned with the subject of lighting in air navigation, the movement for a better international understanding with regard to standards of light, and the dissemination of information regarding the Jubilee of Electric Light, celebrated last year in many countries.

In practically every field of service electric light is continuing to expand in usefulness, but for the most part, as pointed out above, the developments during the past year have not been of a striking nature. Only by looking back over a period of several years can the fact that steady but slow progress is being made in this field or that one be determined. Even though, in this report, no specific comment to such progress in many important fields has been made, the fact that it is being made should not be forgotten.

Application to Marine Work

REPORT OF COMMITTEE ON APPLICATION TO MARINE WORK*

To the Board of Directors:

This Committee's chief activities during the present term have been devoted to an extensive review and revision of Standards No. 45. Having been advised that the stock on hand was practically exhausted, the committee had its choice of reissuing Standards No. 45 in its present form, or of revising the same to incorporate the latest developments and expansion in the marine practise. In view of the fact that Standards No. 45 is now nationally recognized by naval architects, marine engineers, shipbuilders, and ship owners, as the American Standard governing electrical installations on shipboard, and owing to many desired revisions and additions, the committee decided to review all sections of the rules and bring them up to date.

The task of revision was accomplished completely during the present term and the committee has turned over the revised rules to its Subcommittee on Editing. All sections were carefully reviewed by the working subcommittees and the main committee, and have received the required approval. It is expected that the Subcommittee on Editing will complete its work and submit the revised rules to the A. I. E. E. Standards Committee in the early fall of this year, or before.

New sections have been added on brakes, water-tight doors, electric clutches, and the radio direction finder. The section on gyroscopic stabilizers has been expanded to cover practise which is now considered standard.

Where desirable, the subcommittees consulted outside authorities on their subjects. At the committee's request, the Institute of Radio Engineers appointed representatives to cooperate with the subcommittee handling radio.

Our efforts were continued with the Steamboat Inspection Service to obtain classification and rating for electrical operating engineers on shipboard. A few conferences were held with representatives of that organization and some progress of an educational nature was made.

The chief activities in the marine field to which electricity has contributed its share are:

1. Four additional U. S. Coast-Guard cutters having electric propulsive equipment, are now being constructed.
2. Two 26,500-ship-hp., twin-screw turbine-electric liners for the Dollar Steamship Lines, Inc. are now under construction.
3. One 12,600-ship-hp. twin-screw turbine-electric liner was placed in service for the Grace Line.
4. One 6000-ship-hp. twin-screw turbine-electric yacht was placed in service.
5. One 2600-ship-hp. turbine-electric yacht was placed in service.
6. Two 7200-ship-hp., twin-screw turbine-electric drive lake car-ferries were placed in service.
7. Two 2000-ship-hp. tunnel-screw turbine-electric drive, river tow boats, are under contruction.
8. Several small craft now have Diesel-electric drive.

The Jones-White Act is having a decided influence on shipbuilding and several contracts are pending, some of which will use turbine-electric drive. The use of electrical auxiliaries has become standard practise for practically all ships of reasonable size.

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*COMMITTEE ON APPLICATIONS TO MARINE WORK:

W. E. Thau, Chairman,
R. A. Beekman, Vice-Chairman,
J. L. Wilson, Secretary,

Edgar C. Alger,	H. L. Hibbard,	Edgar P. Slack,
H. C. Coleman,	A. Kennedy, Jr.,	H. M. Southgate,
E. M. Glasgow,	J. B. Lunsford,	A. E. Waller,
H. F. Harvey, Jr.,	E. B. Merrian,	Oscar A. Wilde,
C. J. Henschel,	I H. Osborne,	R. L. Witham,
Wm. Hetherington, Jr.,	G. A. Pierce,	W. N. Zippler.
	W. H. Reed,	

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

Applications to Mining Work

ANNUAL REPORT OF THE COMMITTEE ON APPLICATIONS TO MINING WORK*

To the Board of Directors:

In the report made one year ago mention was made of the prediction that both coal and metal mining are entering a new era of development. This has begun and indications point to a continuance of development particularly as to mechanization. We now have references made to some modern mines as being 100 per cent mechanized. Future developments will no doubt modify the scheme of application of mechanical operation in many details. Statistics indicate that an increasing percentage of coal is undercut, drilled, and loaded mechanically. This means that added generating capacity and conductors for distribution will be required. Also, inasmuch as power purchased from the utilities is increasing in use at the mines, the mechanization adds to the utility load.

Pumps

One company[1] installed ten synchronous motor-driven mine pumps from 300 to 600 hp.

Motor Generator Sets

With increasing mechanization more power at the face is required. This has been accomplished in many cases by sets near the face. These are usually controlled by automatic switchboards, which have been simplified by the majority of manufacturers.

Some installations of portable substations have been made.[2] These are adaptable to installations where conditions of loading change rapidly.

Some installations of mercury arc rectifiers have been made, rated 300 kw. at 275 volts.[3]

Shovels

The largest shovel made to date was placed in operation this past year.[4] It has a 15-yd. dipper on 120-ft. boom, weighing 1800 tons with an aggregate of some 5500 hp. in equipment, consisting of 700-kv-a. synchronous motor on multiple mg. set and main hoist operated by two 450-hp. motors, with a number of smaller motors, all handled by Ward Leonard control.

Smaller electric shovels from two to eight yard capacity are rapidly displacing steam shovels in the metal mines, 22 having been purchased by one company since January 1929.

In connection with electric shovels, as well as with other portable equipment, the trailing cables are important. The art of field vulcanizing is being perfected rapidly to take care of break-downs.

Slushers

Motor-driven double-drum slushers generally driven by a 15-hp., three-phase, 440-volt motor, have become a part of the metal miner's equipment.

Mining Machines

Track-mounted cutting machines have found a general use in mechanized coal mines. With such a machine about twice the work per day can be performed as is possible with the shortwall type of mining machine.

Loading Machines

In coal mining there has been some increase in the use of pit-car loaders, where low ceiling and bad roof prevail. However, where conditions permit, the full mechanical loaders have gained in favor. Statistics are not complete, but indications are that some 500 or more units of this type are now in service. There have been many experimental loaders tried out, and there are more now in the process of design and manufacture. The principal problem is one of a mechanical nature, though nearly all designs involve the use of electric drive.

Welding

The mines have been using both electric and gas welding to an increasing advantage. This has been applied to repair work more than to construction work.

Safety Work

The Bureau of Mines has continued to expand its field of work.[5] In 1929 there were 19 approvals, 760 extensions granted and 31 manufacturers holding approvals on "Permissible" motor driven equipment.

The Industrial Commission of Utah has passed Resolution No. 950, providing that nothing except "Permissible" equipment may be used in gaseous mines after Jan. 1, 1932. This will necessitate a considerable amount of new equipment.

One company has displaced electric motors for jigging conveyors at the face and is now using air engines. Another has installed air motors on arc wall cutting machines, instead of electric motors. In both instances this was for safety.

Agitation continues for better lighting. In the metal mines this has been met to some extent by installing 440-volt/110-volt dry type transformers and portable lamps at or near a-c. motor-driven slushers.

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Graham Bright,	L. C. Ilsley,	W. F. Schwedes,
John H. Edwards,	J. E. Kearns,	F. L. Stone,
Frank E. Fisher,	W. H. Lesser,	J. F. Wiggert.
	S. O. Miller,	

1. Susquehanna Collieries Co.
2. Butler Consolidated Coal Co. Furnished by G. E. Co.
3. Glen Alden Coal Co. Equipment by G. E. Co.
4. United Electric Coal Co. Equipment by G. E. Co. and Marion.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

5. See Bureau of Mines Circulars 6997 and 7061.

Many explosions have been started by temporary stoppage of air circulation. This year there has been developed a co-related system of relays, signals,[6] etc., which can be applied to mine ventilation doors, air currents and electrical circuits to perform several functions such as operating a signal, making a graphic record, sounding an alarm, shutting off inside power, etc. This system applied to a gaseous mine would be of material value in avoiding explosion hazards.

6. See *Coal Age*, Feb. 1930, p. 89.

Power Generation

ANNUAL REPORT OF COMMITTEE ON POWER GENERATION*

To the Board of Directors:

The major work of this committee during the past year devolved upon its subcommittee on interconnection, composed of F. C. Hanker, Chairman, and affiliates, several of whom were selected outside of committee personnel to secure broad contact with current problems in the subject and to serve as liaison members on associated engineering committees handling related subjects. Recognition of the technical import of interconnection was initially made by the Power Generation Committee in a symposium of papers presented at the mid-winter convention in 1928, when the subject was treated chiefly from a regional aspect. Experience throughout 1928 and 1929 focused attention upon several problems of the mechanics of operating interconnections, and the subcommittee appointed in 1929 was enabled to obtain for a symposium at the January, 1930, Convention papers on two operating topics which have been investigated with definite results. The other three papers sponsored for the Winter Convention by the subcommittee were just as pertinent, but covered rather the principles of successful service to separate and contiguous load areas in typical metropolitan districts by relating the fundamental plans upon which the electric systems in Chicago, Detroit, and Philadelphia have been developed. These three papers, together with companion papers describing the method of power supply recently adopted in New York City which had been presented under the auspices of the Power Transmission and Distribution Committee at the 1929 Summer Convention, form an excellent compilation of the status of interconnection of power generation sources in large city electric systems. The papers included in the 1930 Interconnection Symposium were:

Controlling Power Flow with Phase-Shifting Equipment. by W. J. Lyman.

Operating Characteristics of Turbine Governors, by T. E. Purcell and A. P. Hayward.

System Connections and Interconnections, Chicago District, by George M. Armbrust and Titus G. LeClair.

The Fundamental Plan of Power Supply of The Detroit Edison Company, by S. M. Dean.

Fundamental Plan of Power Supply in the Philadelphia Area, by Raymond Bailey.

To accomplish the most thorough treatment of the subject of Interconnection, a joint interconnection subcommittee has been proposed by H. R. Woodrow, Chairman of the Power Transmission and Distribution Committee, to be composed of representatives of the committees on Power Generation, Power Transmission and Distribution, and Protective Devices. The purpose of this joint committee would be to keep the three major committees advised of all studies and developments pertaining to the subject, and to facilitate the handling of Institute activities with regard to the many interrelated phases of the interconnection problem. Mr. F. C. Hanker has been designated chairman of this joint subcommittee with the expectation of selecting such associates from the three principal committees as may be in position to assist in the prosecution of this work.

The committee has not undertaken for this year's report a resumé of the status of power generation similar to that prepared last year. The committees in the past four years have concluded for several reasons that a continuous and coherent history of power generation development can be written most advantageously at biennial intervals. The present Committee, while cognizant of the wide scope of its subject, believes that the introduction of new ideas in power plant design, construction, and operation, are principally matters of ensuing development over a period of two to three years rather than of immediate and complete innovations. An attempt to portray yearly significant progress would therefore result in duplication if the committee subject were to be covered thoroughly, or else the yearly resumés would consist of disjointed monographs as might appeal at the time to the individual committee. It is recommended, in consequence, that unity of outline and continuity of discussion be established between successive résumés and that this can best be accomplished by allowing sufficient perspective between reports of a historical nature on the subject of Power Generation.

Pertaining to the frequently recurring question of the general character of survey reports on the subject of power generation, the Committee is indebted to Mr. J. B. Crane who has made a statistical study of the membership common to both the A. I. E. E. and the A. S. M. E. national societies. It was found that in 1928 only 4.6 per cent of the membership of the A. I. E. E. were members of the A. S. M. E., while likewise only 4.7 per cent of the A. S. M. E. membership

*COMMITTEE ON POWER GENERATION:

F. A. Allner, Chairman,
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J. B. Crane,	J. H. Lawrence,	F. A. Scheffler.
N. E. Funk,	W. S. Lee,	A. E. Silver,
W. S. Gorsuch,	F. T. Leilich,	W. F. Sims,
F. C. Hanker,	H. W. Leitch,	A. R. Smith,
C. F. Hirshfeld,	E. B. Meyer,	E. C. Stone,
F. H. Hollister,		R. W. Stovel.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Canada, June 23-27, 1930.

were enrolled in the A. I. E. E. In view of these facts the Committee believes there is unquestionable justification in striving for completeness and representative detail in summary reports of the historical development of power generation, irrespective of contemporary surveys which may be prepared by other societies. It is evident that the A. I. E. E. membership would be inadequately served were this Committee to circumscribe its report to avoid likely duplication of progress reports of A. S. M. E. committees treating similar topics.

Subcommittees on the Rehabilitation of Hydro Plants, and on Electric Power Generation Practises in Industrial Plants, were continued from the previous year, as well as Committee effort to keep in contact with the development of European power plant practise. The economic and engineering aspects of the rehabilitation of steam-electric power plants were admirably discussed in a paper by Mr. C. F. Hirshfeld at the 1929 Summer Convention, and it is the sense of the Committee that a companion treatment of the problems incident to the revamping of hydro developments is indicated by the increasing volume of such work that is now technically possible, and in many instances, economically feasible. Data regarding European high-pressure boiler types included in last year's report, and a paper obtained this year on European hydro practise, have seemed both pertinent and valuable, and the Committee therefore believes that this source of information can be profitably investigated by future committees.

The subcommittee on Electric Power Generation Practises in Industrial Plants, consisting of Messrs. F. A. Scheffler, Chairman, H. W. Brooks, and A. R. Smith, and affiliates from the A. S. M. E., Messrs. Fred M. Gibson, and William F. Ryan, endeavored to get in touch with representative industrial plant engineers for the purpose of discovering the problems of electric power generation peculiar to industrial installations and of learning how the activities of the Power Generation Committee could be of greater benefit in the industries. Accordingly notices inviting correspondence with the subcommittee were placed in the A. I. E. E. Journal, A. S. M. E. *News*, *Power*, *Electrical World*, and *Power Plant Engineering*. In addition, letters were written to various engineers in the coke, steel, paper, automobile, textile, rubber, and soda ash industries for the same purpose. The ensuing correspondence developed suggestions for Institute topics fully appreciated by the subcommittee, but which after review have seemed to the subcommittee to consist almost entirely of topics more related to the work of other technical committees of the A. I. E. E. and of trade and commercial organizations in the various industries, than they are to that of the Power Generation Committee. The subcommittee consequently believes there is no apparent feeling among industrial plant engineers that the services of the Power Generation Committee are not available to them for the presentation of Institute papers on relevant subjects; and in conclusion the subcommittee recommends that it be discontinued after acknowledging the suggestions of its correspondents and offering to facilitate the presentation of such papers as may be prepared, either under its own auspices or through the several Institute technical committees to which the subject matter of the subcommittee's investigation has been transmitted.

The balance of the work of the committee has been undertaken with the idea of securing for Institute persentation papers on the subject of power generation describing recent and salient aspects of power plant design in Europe as well as in this country. The committee is recommending, therefore, as illustrative for this purpose, papers regarding

1. The East River Generating Station of the New York Edison Company.
2. A new system of speed control for a-c. motors.
3. Hydro power practise in Central Europe.
4. Hydraulic and electric possibilities of high-speed adjustable-blade waterwheels for low-head developments.

The first paper named describes a metropolitan power plant in which generators, boilers, and frequency converters of notable size and novel design have recently been installed. The second paper is of interest because the new system of speed control was developed for the regulation of a-c. motor driven auxiliaries in power plants. The paper on European hydro practise is a good exposition of the method of design adopted by European engineers who have had recourse to extensive preliminary model testing of entire hydro developments as well as of component parts. The fourth paper treats of the economic advantages to be derived from the high-speed propeller turbine of the manually and automatically adjustable blade type, through the increased part-gate efficiency, greater reduced-head capacity, and decreased electrical costs, that are possible. The paper foreshadows a wider adoption in this country of the Kaplan turbine that has been successfully applied to low-head installations in Europe.

Power Transmission and Distribution

ANNUAL REPORT OF COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

To the Board of Directors:

The Committee on Power Transmission and Distribution has found its problem sufficiently broad to justify the division of the work into several classes. A subcommittee has been appointed to cover the scope of the problems falling within each class and this year it has been possible to get each one of these problems more carefully defined and the work started in a definite direction.

In practically every phase of the work the subcommittees find their activities closely related to the activities of other committees of the Institute or similar committees in other organizations. Particular attention has been given to the coordination of this work with the work of the other committees in order that unnecessary duplication may be avoided and that none of the important phases will be left out of consideration.

The classifications as handled by the several subcommittees this year are as follows:

A subcommittee, of which Mr. C. T. Sinclair is chairman, has reviewed the problems of the distribution of electrical energy in cities and rural communities.

Mr. Philip Sporn has continued the very active work of chairman of the subcommittee on lightning and insulators.

A subcommittee, of which Mr. R. N. Conwell is chairman, has recently been appointed to review the problems of steel transmission towers and conductors.

The study of the question of interconnection and stability factors has been continued under the leadership of Mr. R. D. Evans as chairman.

The work of the subcommittee on cable development has been very active under the leadership of Mr. T. F. Peterson.

The research work on impregnated paper insulated cables has been continued in the joint subcommittee of the N. E. L. A. Underground Systems Committee, A. E. I. C. Committee on High Tension Cable, and the Committee on Power Transmission and Distribution of the A. I. E. E., with Mr. D. W. Roper, serving as chairman of this joint activity.

Mr. F. M. Farmer has coordinated the activity of the bodies on standardization within the field of power transmission and distribution.

*COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION:

H. R. Woodrow, Chairman,
P. H. Chase, Vice-Chairman,
T. A. Worcester, Secretary,

R. E. Argersinger,	R. D. Evans,	D. W. Roper,
R. W. Atkinson,	F. M. Farmer,	A. E. Silver,
E. T. J. Brandon,	J. H. Foote,	C. T. Sinclair,
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R. N. Conwell,	D. C. Jackson, Jr.,	Philip Sporn,
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L. L. Elden,	G. E. Quinan,	R. J. C. Wood.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

The problem of interconnection and stability factors has engaged several subcommittees in extensive study, and steps have been taken to coordinate this work by the appointment of a joint subcommittee reporting to the Protective Devices Committee, Power Generation Committee, and the Committee on Power Transmission and Distribution of the A. I. E. E., and carrying on its activity in close cooperation with the Power Systems Engineering Committee of the N. E. L. A. Although it is impossible at this time to predict the activities for the coming year, it is thought by all three of the A. I. E. E. committees that this joint subcommittee should be appointed to correlate the work and analyze the problems in this important field.

Distribution

The development of the a-c. low-voltage network has altered the methods of distributing electricity in locations having a large load density. Where tall buildings exist, the problem of distributing the electrical energy throughout the building has reached the proportions of street distribution which has resulted in the introduction of vertical networks within the building.

The rural communities distribution problem has brought forth some interesting solutions to insure reliable service and at the same time keep the cost within the permissible limits.

Lightning and Insulators

Additional instruments have become available during the past year in studying lightning. These are the lightning stroke recorder which measures the current in a lightning stroke, and the field intensity recorder which records the electrostatic field (kv. per ft.) under the cloud. With these instruments have been recorded currents reported in the order of from 50,000 to 175,000 amperes in a lightning stroke, and field gradients as high as 85 kv. per ft. on an insulated antenna. Field gradients on transmission lines as high as 52-kv. per ft. of height have also been recorded by surge recorders.

The cathode-ray oscillograph, during the past year, has yielded some 150 field records of actual lightning voltage wave shapes on transmission lines. Analysis of these records show a maximum crest voltage of 1260 kv. wave fronts in the order of one to over 80 microseconds, and a total length, until the wave falls to zero, of as high as 150 microseconds. These data comprise a large increase of this type of information over the two records of natural lightning secured in the previous year. Lightning voltages up to 15.2 times normal line voltage to neutral have been recorded; and switching surges as high as 5.5 times normal were observed.

Additional data on the attenuation of both natural and artificial lightning have been obtained which further confirm past data and theory, showing the rapid

decrease in the crest value of lightning waves in excess of corona voltage as they travel away from their point of origin. The lightning generator has been used extensively in the field the past year, three such installations being in use for a large part of the lightning season.

A study of lightning attenuation has also been carried on to determine the effect of steepness of wave front and polarity, of ground wire size and resistance, and also the effect of counterpoises. Field studies have also been started to show the behavior of traveling waves at the juncture of cables and open wire lines.

Extensive work has been done in the field measuring the surge impedance of actual lines, and determining the effect of tower footing resistances under lightning conditions.

Line Design from the Lightning Point of View. The benefits derived from the use of substantially installed ground wires on steel tower lines are now generally accepted. In some cases more than one ground wire has been employed; but the location of additional ground wires is still an open question due to the lack of definite knowledge, at the present time, as to whether the direct or induced lightning stroke is more important to protect against on high-voltage lines.

The insulation of wood pole lines from the lightning aspect has been receiving attention, and there are now in service several such lines using wood crossarm braces, insulated guy wires, and pole ground gaps, in an attempt to raise the lightning flashover of the line and at the same time minimize the possibility of pole and crossarm splitting. The fused grading shield is another design feature which has been given further study in service the past year. In one case the tower footing resistance of a 56 mile, 132 kv. steel tower line has been materially lowered by auxiliary ground rods in an attempt to improve the lightning performance of the line. Similar work is also being done on another high-voltage 33-mile line at the present time. Over-insulation of steel tower lines, materially higher than past practise, is not making much headway although one important line has been designed for extra line insulation should this be found desirable.*

Presentation of Data and Results. During the year the Committee has sponsored, wholly or in part, groups of papers at three A. I. E. E. conventions, namely, the Winter Convention in February 1930, where eight papers were presented in the lightning group, the Springfield Convention in May, 1930, where five papers were presented at the transmission session, and the Toronto Convention in June, 1930, where seven papers were presented on rationalization of transmission system insulation strength. Practically all of these papers deal with this most important subject of lightning, its effect on the transmission system, and protective measures to bring it under control.

*Another method of lowering the tower footing resistance has been tried on a 220-kv. line. This consists of connecting the tower base to buried cable which in turn extends some distance away from the tower.

Some valuable data have been obtained which have not yet been analyzed and assimilated. It is the intention of the committee, however, not only to cooperate in every way possible, to have these data as well as future information made available to the electrical field for immediate use, but also to encourage the undertaking of new investigations where needed and to have the results of these investigations made available to the Institute Membership.

1930 Lightning Investigations. Field investigations of lightning is being carried forward on an increased scale. The instruments available and being used include:

1. Klydonographs and surge recorders.
2. Cathode ray oscillographs.
3. Lightning generators.
4. Lightning stroke recorders.
5. Surge indicators.
6. Field gradient recorders.

The work planned includes a wide field of investigation in which are studies on:

1. Lightning voltage magnitude.
2. Wave shape of natural lightning.
3. Attenuation and change of wave shape of lightning.
4. Effect of tower footing resistance.
5. Effect of counterpoises.
6. Determination of cloud field gradients.
7. Lightning voltage behavior at terminals of open wire line and cable.
8. Current in lightning strokes.
9. Importance of direct and induced strokes.
10. Records of insulator flashovers caused by lightning.
11. General investigation on distribution systems.

Insulator Situation. The present situation in the insulator field indicates a feeling among manufacturers that most of the troubles experienced in the past have been overcome. A summary of their attitude shows that:

1. Porous porcelain, under present manufacturing conditions, should seldom if ever be encountered.
2. Raw materials from selected sources and careful factory inspection have greatly improved the product.
3. Present controlled factory processes of mixing, forming, and firing the porcelain have resulted in a uniform product.
4. Porcelain as made today is practically free from aging.
5. Insulators may deteriorate due to the method of hardware attachment and stress distribution within the porcelain but this problem, it is felt, is being worked out satisfactorily.
6. The expected life of suspension insulators should be practically equal to that of the line or towers.
7. The use of high strength units appears to be making considerable headway.

The manufacturers, with their close attention to the various steps and processes in the manufacture of porcelain, and to the design and assembly of hardware, and with their knowledge of the actual results obtained on their product in the field, seem to have reason for feeling satisfied with conditions as they are. On the other hand, a piece of equipment subject to as many variables as is a completely assembled porcelain insulator, with each variable offering possibilities for deleteriously affecting the product, particularly after a lapse of time, is not a product on which vigilance can be relaxed at any time. It is believed that accelerated life tests and accurate loss measurements on porcelain insulators offer a means for determining in advance the probable performance and life of modern insulators, and of variations of them. Again, it is believed that it is possible to incorporate refinements in the control of temperatures and of humidity involved in the various steps of the insulator manufacture that will further decrease the variability in the product and increase the possibility of longer life. To these problems the Committee expects to give serious consideration during the coming year.

BIBLIOGRAPHY

The entire subject of lightning is one that is very much alive at the present time, and a great deal of work is being done on it and many data have been published. With a subject as active as this, it is obviously impossible to cover in this report all the phases of the problem and all the progress made during the past year. A bibliography, by no means complete, is given below for the use of those who may care to go completely into the details of the work that has been carried out during that time. The extensiveness of the list is adequate proof as to the amount of interest shown and work done on the above subject; and while the list is not complete, it is believed that it covers the more important contributions which have been made, and all those of importance which have come to the attention of the Committee.

1. *Effect of Transient Voltages on Power Transformer Design*, by K. K. Palueff, A. I. E. E. Trans., Vol. 48, July 1929, p. 681.

2. *Fused Arcing Horns and Grading Rings*, by Philip Stewart, A. I. E. E. Trans., Vol. 48, July 1929, p. 891.

3. *Cathode Ray Oscillograph Study of Artificial Surges on the Turners Falls Transmission Line*, by K. B. McEachron and V. E. Goodwin, A. I. E. E. Trans., Vol. 48, July 1929, p. 953.

4. *Lightning, Progress in Lightning Research in the Field and in the Laboratory*, by F. W. Peek, Jr., A. I. E. E. Trans., Vol. 48, April 1929, p. 436.

5. *Theoretical and Field Investigations of Lightning*, by C. L. Fortescue, A. L. Atherton, and J. H. Cox, A. I. E. E. Trans., Vol. 48, April 1929, p. 449.

6. *1927 Lightning Experience on the 132-Kv. Transmission Lines of the American Gas and Electric Co.*, by Philip Sporn, A. I. E. E. Trans., Vol. 48, April 1929, p. 480.

7. *Power Transmission and Distribution Committee Report*, by H. L. Wallau, Chairman, A. I. E. E. Trans., Vol. 48, April 1929, p. 487.

8. *A Graphical Theory of Traveling Electric Waves between Parallel Conductors*, by V. Karapetoff, A. I. E. E. Trans., Vol. 48, April 1929, p. 508.

9. *Impulse Insulation Characteristics of Wood Pole Lines*, by H. L. Melvin, A. I. E. E. Trans., Vol. 49, January 1930, p. 21.

10. *Effect of Surges on Transformer Windings*, by J. K. Hodnette, A. I. E. E. Trans., Vol. 49, January 1930, p. 68.

11. *Theory of a New Valve Type Lightning Arrester*, by J. Slepian, R. Tanberg, and C. E. Krause, A. I. E. E. Trans., Vol. 49, January 1930, p. 257.

12. *Ionization Currents and the Breakdown of Insulation*, by J. J. Torok and F. D. Fielder, A. I. E. E. Trans., Vol. 49, January 1930, p. 353.

13. "Lightning," by F. W. Peek, Jr., *General Electric Review*, November 1929, p. 602; December 1929, p. 691.

15. "Transmission Line Insulation and Field Tests Pertaining to Lightning," by W. W. Lewis, *General Electric Review*, July 1929, p. 364.

16. "Reflection of Transmission Line Surges at a Terminal Impedance," by O. Brune, *General Electric Review*, May 1929, p. 258.

17. "The Lightning Arrester and Factors Affecting Its Performance and Application," by H. M. Towne, *General Electric Review*, August 1929, p. 428.

18. "Cathode Ray Oscillograph Study of the Operation of Choke Coils on Transmission Lines," by K. B. McEachron, *General Electric Review*, December 1929, p. 668.

19. "High-Voltage Surge Oscillograph," by J. J. Torok and F. D. Fielder, *The Electric Journal*, July 1929, p. 320.

20. "Testing Lightning Arrester Grounds," by Edward Beck, *The Electric Journal*, July 1929, p. 317.

21. "Ungrounded *vs.* Grounded Neutral Systems from the Standpoint of Lightning Protection," by Edward Beck, *The Electric Journal*, February 1929, p. 50.

22. *Lightning on Transmission Lines*, by J. H. Cox and Edward Beck, A. I. E. E. Trans., Vol. 49, July 1930.

23. *Surge Characteristics of Insulators and Gaps*, by J. J. Torok, A. I. E. E. Trans., Vol. 49, July 1930.

24. *Lightning Investigations on Lines of Public Service Electric & Gas Co.*, by R. N. Conwell and C. L. Fortescue, A. I. E. E. Trans., Vol. 49, July 1930.

25. *Lightning Voltages on Transmission Lines*, by R. H. George and J. R. Eaton, A. I. E. E. Trans., Vol. 49, July 1930.

26. *Traveling Waves on Transmission Lines with Artificial Lightning Surges*, by K. B. McEachron, W. J. Rudge, and J. G. Hemstreet, A. I. E. E. Trans., Vol. 49, July 1930.

27. *Lightning Investigation on 220-Kv. System of Pennsylvania Power and Light Co.*, by Nicholas N. Smeloff and A. L. Price, A. I. E. E. Trans., Vol. 49, July 1930.

28. *Lightning Investigation on the Ohio Power Company's 132-Kv. System*, by Philip Sporn and W. L. Lloyd, Jr., A. I. E. E. Trans., Vol. 49, July 1930.

29. *Lightning Investigation on Transmission Lines*, by W. W. Lewis and C. M. Foust, A. I. E. E. Trans., Vol. 49, July 1930.

30. *Transmission Research and Design with the Field as a Laboratory*, by F. E. Andrews and C. L. Stroup, A. I. E. E. Trans., Vol. 49, July 1930.

31. *Calculation of Protection of a Transmission Line by Ground Conductors*, by H. B. Dwight, A. I. E. E. Trans., Vol. 49, July 1930.

32. *A New Transmission Line Construction Post Type Towers*, by P. H. Thomas, A. I. E. E. Trans., Vol. 49, July 1930.

33. *Arcing Grounds and the Effect of Neutral Impedance*, by J. E. Clem, A. I. E. E. Trans., Vol. 49, July 1930.

34. *Fused Grading Shields*, by H. A. Frey and E. M. Skipper, A. I. E. E. Trans., Vol. 49, July 1930.

35. *Essential Factors in the Coordination of Line, Station, and Apparatus Insulation*, by A. E. Silver and H. L. Melvin, A. I. E. E. Toronto Convention, June 1930.[2]

36. *Rationalization of Transmission Insulation Strength II*, by Philip Sporn, A. I. E. E. Toronto Convention, June 1930.[2]

37. *Standards of Insulation and Protection for Transformers*, by J. Allen Johnson and Edwin S. Bundy, A. I. E. E. Toronto Convention, June 1930.[2]

38. *Coordination of Insulation as a Design Problem*, by G. D. Floyd, A. I. E. E. Toronto Convention, June 1930.[2]

39. *Rationalization of Station Insulating Structures with Respect to the Insulation of the Transmission Line*, by C. L. Fortescue, A. I. E. E. Toronto Convention, June 1930.[2]

40. *Recommendations on Balancing Transformer and Line Insulation on Basis of Impulse Voltage Strength*, by V. M. Montsinger and W. M. Dann, A. I. E. E. Toronto Convention, June 1930.[2]

41. *The Effect of Transient Voltages on Dielectrics IV. Law of Impulse Sparkover and Time Lag*, by F. W. Peek, Jr., A. I. E. E. Toronto Convention, June 1930.[2]

42. "The Present Status of the Problem of Lightning Protection," by Professor A. Matthias, *Elektrotechnische Zeitschrift*, October 1929.

43. "Protection of Electrical Systems Against Overvoltages," (Report of Electrical Institute of Technology College Aachen), by Eugene Flegler, *Elektrotechnische Zeitschrift*, January 1930.

44. "Overvoltages in Electrical Systems," by K. Berger, *Bulletin of Schwerzerischer Electrotechincher Verein*, February-March, 1930.

Steel Transmission Towers and Conductors

The numerous unsolved problems in connection with the design of steel transmission towers and conductors indicate the desirability of lending aid and encouragement to research and development work, which work must be coordinated with that carried on by other associations and development bodies. Progress can be made in the matter of simplification and standardization and this again requires the cooperative efforts with other associations and standardizing bodies.

In particular, the following problems are under review at the present time and these will be brought before the Institute as soon as the studies have indicated a clearer presentation of the problems or their solution.

1. Definition of terms and the elimination of ambiguous expressions in specifications.
2. Study of clearances required between towers and conductors due to the electrical and mechanical conditions imposed upon the line.
3. Study of protective coatings.
4. Study of the electrical and mechanical features of ground wires in cooperation with the Subcommittee on Lightning and Insulators.
5. Study of the effect of size or amount of steel exposed to a conductor on flashover.
6. Study of whipping, vibration, and impact of conductors including devices for the reduction or elimination of these phenomena.

Interconnection and Stability Factors

Interconnections and the increases in the extent of power systems have raised a number of important questions. Of these, the measures necessary to insure reliability of operation are of the greatest importance. Technically, this means that the system, including interconnecting lines, must be so designed and operated that synchronism will be maintained between generating units and synchronous machines of the load. In other words, interconnected systems must possess adequate stability under normal operating conditions, and also during times of system disturbances.

An outstanding development in interconnection and stability is concerned with the application of high-speed circuit breakers and relays. Synchronous equipment, because of the inertia, cannot lose synchronism instantaneously. Consequently, the transient stability limits of a system may be materially increased by isolating the faults promptly. This is particularly true of interconnections since fast isolation of faults on either system minimizes the abnormal load thrown on the interconnection. The use of high-speed circuit breakers and relays offers very considerable promise for improving system stability.

Oil circuit breakers which have been available in the past for use on high-voltage systems, have been relatively slow in their operation, their average operating time being of the order of 20 to 40 cycles. The new high-speed breakers recently brought out are capable of isolating a fault in from 8 to 12 cycles from the instant the trip coil is energized until the arc is extinguished. Heretofore, protective relays, being of the induction type, have been relatively slow in their operation. The new high-speed relays will have a maximum operating time of one or two cycles at the most, and even less time for the relays located close to the fault.

Double-winding generators have received considerable attention in connection with metropolitan type systems for reducing the short circuit currents, and at the same time maintaining adequately high synchronizing power.

The use of quick response excitation for machines on transmission systems has become fairly well established with the exciter response rate being usually arranged for 200 to 600 volts per second. In special situations, higher response rates may be found desirable especially in connection with synchronous condenser installations.

In connection with certain major transmission projects, there has been discussion of the use and effects of damper windings. It is probable that the ideas on the use of damper windings will be clarified by papers to be presented in the near future.

The relative merits of different methods of grounding from the standpoint of system stability have been considered. Some operating companies have found it desirable to limit the severity of faults to ground at certain locations, and have grounded only a part of the transformer banks at a given location, or have introduced neutral impedance devices. In general, for major transmission systems, solidly grounding has been viewed favorably from the protection standpoint and unfavorably from the stability standpoint. The recent development of high-speed circuit breakers and relays tends to remove the latter objection, thus leaving the

2. A. I. E. E. Trans., Vol. 49, Oct. 1930.

choice of the method of grounding to be determined by consideration of protection.

System stability is a subject which has been before the industry for several years. Several of the measures which have been proposed to increase stability have actually been tried out on power systems, and new methods of operation are being put into effect. Thus, the operating data accumulating from year to year provide an increasing amount of information as a guide to the design of power systems with increased stability. A few examples in this connection will be cited. The scheme of system connections known as "synchronized at the load," has now received over a year's operating experience in New York City, and very satisfactory results in both stability and reliability of operation have been secured, the indicated margins of stability being more than adequate. In the southeastern district, one operating company has obtained increased reliability of operation by several means including synchronizing of hydro-generators and transmission lines only at load points, grounding only a part of the transformers at a station, installing quick response excitation. Observations on the performance of systems under short circuit tests on high-speed circuit breakers and relays have indicated that the shocks to the system are much reduced by high-speed isolation of faults.

During the past year, the subject of prime-mover governor control has received attention, particularly as a result of operating experience with automatic frequency control. This apparatus provides an arbitrary distribution of prime-mover input increments required by an undetermined distribution of load increments. Hence this apparatus, while of some advantage from the stability standpoint, does not insure the ideal control of the distribution of prime-mover input. This should not be serious, however, since with complete application of automatic frequency control to a system, generating units will not ordinarily carry loads below 50 or 60 per cent of rating.

The a-c. calculating devices which have been developed permit an accurate determination of current, voltage, power, and phase angle relations in an a-c. power system. These devices are an outgrowth of the d-c. calculating tables and the miniature a-c. systems which have been used in the past to represent power system networks.

The a-c. calculating device already has found a wide field of application in making system analyses; for example:

1. Normal System Studies: Determination of current distribution, power distribution, and voltage conditions in a-c. power system networks. Also, studies of voltage and power factor control.

2. System Fault Studies: Determination of magnitude and distribution of current under three-phase, single-phase, and line-to-ground fault conditions. If the faults are unsymmetrical the quantities can be determined by the use of the "symmetrical component" method.

3. System Stability Analysis: Determination of steady-state power limits, power angle curves, and studies of transient conditions by point-by-point analysis.

The interest in the analysis of power system problems on the part of engineers who deal with system planning and operation is increasing. In this connection reference may be made to a group of papers on interconnection presented at the Winter Convention under the auspices of the Power Generation Committee which include a discussion of the system connections in relation to stability. This interest was also reflected at the colloquium on power circuit analysis held at the Massachusetts Institute of Technology June 10 to 22, 1929, and at the annual fall meeting of the Great Lakes division of the N. E. L. A. held at Madison, Wis., October 23 to 26, 1929. The papers presented a general review of the situation at the time as related to the solution of power circuit problems with particular emphasis on those involving system stability.

The desirability of a standardized terminology for stability investigations is being reviewed by a group of the subcommittee with a view to submitting a report through the regular channels to the proper standardizing committee.

Cable Development

This year's developments have been largely along lines of standardization, simplification, and reduction of rudimentary and experimental designs and methods to economic and practical feasibility. Such advances or radical departures from accepted practises as have appeared can be ascribed to the ever present urge to meet certain economic conditions or to the need for adaptation to the new installation and operation requirements which developments in other fields evoke, rather than to fundamental inherent evolution. For example, a-c. network services to tall buildings call forth vertical riser cable designs for high voltage and long suspension. Interconnection of operating companies may present unprecedented problems in submarine cable transmission. Change-over from open wire overhead construction necessitates substitution of new types of aerial and buried cable. Radio communication with planes in flight prompts studies and developments of shielded wire and cable to prevent interference, and so on.

Throughout the past year attention has been paid to what may be termed the mechanics of cable installation and operation. The fact that failures due to inherent causes constituted such a small percentage of the total, served to emphasize the importance of these aspects of cable use. Although some improvements have been made results which appear below indicate that there is still a wide enough spread between inherent and non-inherent failures to justify very close study on the part of operating companies.

Research. Cable and dielectric researches as described in last year's report have been continued unremittingly. Already the results of coordination are manifesting themselves in improvement in manufacture and operation. Moreover, they have in other instances opened avenues of progress in standardization, etc.

At the present time a subcommittee of the Underground Systems Committee of the N. E. L. A. is engaged in the preparation of rating tables for cables installed under varying conditions. Other groups are working up tables of thicknesses for rubber, varnished cambric and paper cable.

Although practises abroad do not allow of as high temperature of cable operation as are met with in this country, and undoubtedly cable is therefore not used so severely as it is here, the fact remains that some engineers attribute much of the trouble encountered in operation to voids developed and mechanical stresses set up as a result of the tendency of copper conductors to open when longitudinal thermal expansion is constrained. Special conductors and tensioning devices have been designed to counteract these movements. Information on the results of operation will probably be available to the industry at large and will certainly be watched for with interest. In the meantime it would be well to have our local inspection forces pay particular attention to this phase of cable failures in an effort to explain those which may have fallen too readily in the unknown class.

Inspection, Testing, and Specifications. There have been no special developments in testing and inspection practise in connection with underground cable. Improvement in technique continues slowly, resulting in greater accuracy and more reliable results. In particular long-time, high-voltage tests are being made more carefully and greater attention is being given to the results of such tests. A standard method for measuring thermal conductance of cable is being developed at Massachusetts Institute of Technology in connection with extensive research on thermal insulation. Moderate variations in the thermal conductance of the insulation of underground cables is not in itself a very important matter but it is possible that this quantity can be used as a measure of thoroughness of impregnation. If so, the development of a simple practicable procedure for measuring it in connection with acceptance testing is desirable.

Summaries of a large amount of inspection and test data collected in connection with the inspection of over 9,000,000 feet of paper-insulated cable are reported in the annual report of the Underground Systems Committee, N. E. L. A., for the year 1929. These data show a continued downward trend in the percentage of deficient cable from over 20 per cent in 1923 to less than 3 per cent in 1929. During that period there has been a steady increase in dielectric strength from less than 300 volts per mil in 1923 to over 500 volts per mil in 1929. There have been corresponding improvements in other characteristics.

Greater effort is being made to obtain more accurately the very valuable information which is available in the service records of the companies operating underground cable systems. In particular, more detailed studies are being made of the probable causes of failures. Many data covering cable failures during 1929 are thoroughly analyzed in the report of the Underground Systems Committee referred to above. Incidentally, it may be noted that these studies confirm the improvement in quality of cable indicated by the inspection and test data. Failures due to causes inherent in the cable were, in the calendar year 1929, less than 1.5 per 100 miles of paper-insulated, underground cable rated at over 7500 volts. In 1926 this figure was nearly 3.0. The rate, including all failures for all causes, has decreased from over 9 to nearly 7 in the same period. The grand total rate of failure in 1929 for underground, paper-insulated cable systems, including joints, was a little less than 12 per 100 miles.

The status and developments during the year in respect to specifications and other standards dealing with wire and cable are referred to elsewhere in this report.

Development in Practise. The records for the year 1929 again bear witness to the fundamentally sound bases for designs of oil-filled 132-kv. cable. The 18 miles installed in New York and Chicago (referred to in previous reports) have now continued in operation without electrical failure for a period of two and one-half years. Several installations akin to these were made during the past year and are worthy of note at this time.

In New York a second 132-kv. oil-filled line, 12 miles in length, was installed paralleling the first one built in 1927. In Chicago approximately three additional miles of oil-filled cable were placed in service. The outstanding feature of these installations as contrasted with those previously made is that the cable was shipped impregnated and oil-filled so that the only field impregnation necessary was a short treatment of the joints. This, together with the development and use of horizontal stop-joints, effected a considerable reduction in the time required for installation. In both cases sections of approximately 1800 ft. were employed between stop-joints. In Chicago, however, about one-half of the new cable was arranged with practically all joints of the positive stop, condenser type. As a result of the use of shorter sections, smaller volumes of oil have to be handled and lower hydrostatic pressures are encountered. This allows of the introduction of a smaller hollow core and a modified sheath construction.

Of the several unique types of cable installations made or operated during the year, the following are worthy of particular note:

In Syracuse approximately 3000 ft. of three-conductor oil-filled, 33-kv. cable were placed in service.

An especially notable installation of high-voltage submarine cable was made between Deep Water, N. J. and Pigeon Point, Delaware, on the Delaware River. Eight lengths, each 4075 ft. without splices, of single-conductor, paper-insulated, leaded and armored cable, rated at 75 kv., were installed for operation at 66 kv. This is understood to be the highest voltage submarine crossing of its kind in the world and uses the longest continuous lengths of paper and leaded cable.

10,000 feet of multiple conductor buried cable installed at Birmingham, Alabama, have continued to give satisfactory service at 44 kv. during the year. The construction of the cable is unusual in that the insulated conductors are individually leaded before the three are cabled together and protected with jute and flat steel tape over-all.

The introduction of new methods of supplying tall buildings in the New York metropolitan district with power had led to the design and installation of several types of multiple conductor vertical riser cables for operation at 13.8 kv. Although rubber, varnished cambric, and composite varnished cambric and rubber have found uses in this field, other details are quite uniform. In general, the insulated conductors are shielded with copper tape and cabled without the use of a lead sheath to hold them together. Steel binder tape, jute, and round wire armor serve this purpose and the latter allows of single point support without undue strain on copper conductors or insulation.

Of late there has been a marked tendency toward the use of various types of buried cable. These have been of the conventional makeup as well as numerous variations from this in the form of non-metallic sheathed cable. Although the latter have found quite general acceptance for street and airport lighting projects, experiments are now being conducted to determine their advisability for a-c. secondary network mains. There have recently been installed 66,000 ft. of 4/0 non-magnetic buried cable to serve an area in the metropolitan district which has a moderate load density.

Shielded multiple-conductor cable for transmission continues in increasing favor throughout this country. The field which it dominates has widened and now there are many installations for use at voltages as low as 13.8 kv. The extended use of this cable has been in a measure accelerated by the fact that manufacturers have expressed their willingness to guarantee operation of the so-called type "H" cable at the same maximum temperature as single-conductor cable.

Papers and Future Projects. Among the many problems being considered by this and other committees engaged in similar work, are a comparison of the relative merits of aluminum and copper for transmission and distribution cable and a study of the economics of buried cable installations. The last mentioned had been begun by a subcommittee of the Underground Systems Committee of the N. E. L. A. and is now being carried on with our cooperation.

BIBLIOGRAPHY OF 1929 TECHNICAL ARTICLES ON UNDERGROUND CABLE*

The following bibliography of the 1929 technical papers on underground cable and allied subjects may be of interest. Although many of these are theoretical in their nature and apply particularly to dielectrics, the committee wishes to anticipate the presentation of several other papers now in the course of preparation. Three of these, (one is on current carrying capacity of cable and another on cable joint design), are intended to fill a need for more practical and tangible information on cable use.

TRANSACTIONS OF A. I. E. E.

Lee, *Calculation of the Capacitance between Two Wires of a Three-Conductor Cable,* January 1929, p. 125.

Dwight, *Bessel Functions for A-C. Problems,* (Science Abs. No. 2146, 1929), p. 812.

Dawes, Reichard, and Humphries, *Ionization Studies in Paper-Insulated Cables—II,* April 1929, p. 382.

Davis and Eddy, *Problems in High-Voltage Cable Development,* April 1929, p. 373.

Kitchin, *Power Factor or Dielectric Constant in Viscous Dielectrics,* April 1929, p. 495.

Bailey, *Heat Flow from Underground Electric Power Cables,* January 1929, p. 156.

Schurig, Kuehni, and Buller, *Losses in Armored Single-Conductor Lead-Covered A-C. Cables,* April 1929, p. 417.

J. Whitehead, *Insulation: The Opportunity for Research,* January JOURNAL 1929, p. 27.

Whitehead and Marvin, *Anomalous Conduction as a Cause of Dielectric Absorption,* April 1929, p. 299.

Williams and Murphy, *The Predominating Influence and Electrolytic Material upon Textiles as Insulators,* April 1929, p. 568.

W. W. Houston, *Theory of Electrical Conductivity,* January 1930, p. 30.

Halperin and Miller, *Reduction of Sheath Losses in Single-Conductor Cables,* April 1929, p. 399.

Burns and Treed, *Corrosion of Cable Sheath in Creosoted Wood Conduit,* January 1929, p. 166.

Electrical World

Franklin and Mackay, "Today's Knowledge of Cables," Vol. 93, p. 335.

Fielder and McAuley, "Time Log of Breakdown," Vol. 94, p. 1019.

Whitehead, "Mechanism of Dielectric Loss and Breakdown," Vol. 94, p. 1083.

Sherman, "Tests on Paper Cables," Vol. 94, p. 277.

"Twelve Submarine Cables Laid Together," Vol. 94, p. 631.

"Protecting Shore Ends of Submarine Cable," Vol. 94, p. 635.

"Joining Two Big Systems," Vol. 95, p. 382.

"66,000-Volt Atami Cable," Vol. 93, p. 1342.

McCabe, "Water Penetration in Cable Insulation," Vol. 92, p. 1034.

"Cable Sheath Corrosion," Vol. 92, p. 1282.

Murray, "Cable Sheath Corrosion," Vol. 92, p. 1295.

Journal of I. E. E.

Brown and Sparing, "Prevention of Ionization in Paper Dielectrics," Vol. 67, p. 968.

Cramp and Harvey, "Sheath Losses in Single Core Single-Phase Cables," Vol. 67, p. 335.

Brockbank and Webb, "Sheath and Armor Losses in Single Core Cables for Single-Phase and Three-Phase Transmission," Vol. 67, p. 337.

Wedmore, Morgan & Whitehead, "A Critical Study of a Three-Phase System of Unarmored Single Conductor Cable," Vol. 67, p. 359.

Journal of Franklin Institute

Clark, "Properties of Dielectrics: Dielectric Constant," p. 17.

*Courtesy D. M. Simons.

Electrician

Gillett, "Dielectric Structure and Behavior," Vol. 103, p. 423.

Crompton and Ekstroem, "Overhead Lines or Underground Cables?" Vol. 103, p. 567.

Elsdon and Dew, "20-Kv. Underground Transmission System of Crown Mines Ltd.," Vol. 105, p. 598.

Electrical Review

Beavor, "The Physical Behavior of Lead Sheaths in Relation to Failures of High-Voltage Cables," Vol. 104, p. 96.

Wood, "High-Pressure Cables," Vol. 104, p. 370.

Martinez, "Underground Super-voltage Cables," Vol. 104, p. 905.

Miscellaneous

Lewis, "Grounding the Neutral through Resistance or Reactance," *Gen. Elec. Review*, p. 318.

Hunter and Watson, "Dielectric Disturbances Arising in Super-tension Multi-Core Cables from the Thermal Expansion of Conductors," *Proceedings* of International Conference on High-Voltage Systems, Paris.

Archiv für Elektrotechnik

Haas, "On the Maximum Voltage Gradient in Ordinary Three Conductor Cable," Vol. 21, p. 458.

Dmitriew and Walther, "Breakdown of Oil Impregnated Paper Insulation," Vol. 21, p. 488.

Halbach, "Investigations of the Breakdown and Losses in Some Solid Insulating Materials," Vol. 21, p. 535.

Smurow, "The Physical Characteristics of Electrical Phenomena of Homogeneous Insulation," Vol. 22, p. 31.

Suckow, "Dielectric Phenomena," Vol. 22, p. 104.

Nikuvadse, "Conduction through Dielectrics at Field Strengths up to Breakdown Strength," Vol. 22, p. 283.

Inge and Walther, "Breakdown of Solid Insulating Materials," Vol. 22, p. 488.

Dmitriew and Walther, "Breakdown of Oil Impregnated Paper Insulation," Vol. 21, p. 488.

Halbach, "Electric Strength and Dielectric Losses of Solid Insulating Materials," Vol. 21, p. 535.

Revue Générale de L'Electricité

"Determination of the Dielectric Constant of Imperfect Insulation," Vol. 26, p. 445.

L'Elettrotecnica

Bosone, "On the Experimental Determination of the Capacity of Lead Covered Multi Conductor Cables," p. 705.

Sameda, "Solid Dielectrics in the Industry," p. 14.

Emanueli, "Installation of High Tension Cable," p. 609.

Elektrotecknik und Maschinenbau

Boning, "Experimental Determination of Voltage Distribution in Insulating Materials," p. 613.

Elektrotechnische Zeitschrift

Gyemont, "Phenomena of Motion in Dielectrics at High Voltage," p. 1225.

Birnbaum, "Cables for Mines," p. 1550.

"Three-Conductor 65-Kv. Cable," p. 865.

Impregnated Paper Insulated Cable Research

Research work of various types continue unabated in this important field. It is being carried on under many different auspices. Some of it is of a character which justifies formal reports either periodically or at irregular intervals. The progress of other projects, for one reason or another, cannot be formally reported. All of the activities, however, are serving the purpose of research, that is, the increase in knowledge in respect to impregnated paper insulated cable. A very considerable part of the advancement in the art of underground, high-voltage power transmission is undoubtedly the tangible result of the large amount of research work that is being carried on.

The research projects directly under the sponsorship of the impregnated paper insulated cable research subcommittee have been actively continued during the year. The work at Massachusetts Institute of Technology on the rate of deterioration of impregnated paper was formally completed with the publication by the National Electric Light Association in July, 1929, of the results found for wood pulp paper (N. E. L. A. publication No. 289-87, July 1929). The findings on manila paper were published in the A. I. E. E. JOURNAL, May, 1925, and in the annual report of the N. E. L. A. Underground Systems Committee for 1927. During the past year, the development of a standard test procedure for determining the thermal conductance of high-tension cable has been under way at M. I. T. and it is expected that a final report will be available during 1930.

The work at Johns Hopkins University under Professor Whitehead continues on the original assignment, a study of the effects of residual air and moisture in the insulation of high-tension cable. Progress reports are made from time to time in the form of papers before the Institute; the last one was presented at the Baltimore regional meeting in Baltimore, April, 1928 (A.I.E.E. TRANS., Vol. 47, July 1928, p. 826. The relation between the amounts of residual air and moisture, respectively, and various electrical properties have been pretty well established for the particular materials used. The work for over a year has been devoted to obtaining the relation of these residuals and the life of the insulation under high stress. Much difficulty has been encountered in getting thoroughly satisfactory results and much time has been expended in developing the technique of preparing test samples which will yield thoroughly reliable results under long-time tests. Furthermore, a large number of test samples must be prepared and tested in order to establish the desired relation beyond question. This work will be reported by suitable publication when the final conclusions are obtained.

Professor Dawes at Harvard University has continued the study of the characteristics of ionization in the insulation in paper-insulated, high-tension cable. A third progress report on this work was presented at the Winter Convention in January of this year.

In the aggregate, a large amount of experimental research work in high-tension cable is being done by the central station companies, some of it of a fundamental character and of a very high order. These researches are being carried on both by the company staffs and at universities. Conspicuous among the utilities carrying on research work are the Brooklyn Edison Company, the Detroit Edison Company, and the Commonwealth Edison Company. The last also

joins with the other Insull companies in supporting the Utilities Research Commission, which sponsors a large number of fundamental researches at universities, and the Bureau of Standards. Several of these are on high-tension cable problems.

Among the many research projects being carried on by the utilities may be mentioned the following:

1. Production of very highly refined and treated oils and study of the electrical characteristics and stability of such oils.
2. Study of high-frequency discharges which accompany ionization in insulation and their effect.
3. Systematic study of the performance of various types of cable for 132-kv. service.
4. Elimination of sheath losses in single conductor, high-voltage cable.
5. Study of mechanical properties of cable sheaths with a view to their improvement.
6. Development of method of detecting ionization at any part of a cable.
7. Studies of the fundamental properties of dielectrics used in cable.
8. Studies of the effects of long-time application of electric stress to the cable-insulating materials under various pressure conditions,—rate and kind of gas evolved, change in electrical characteristics, etc.
9. Continuous studies of cable in service as to rate and kind of gas evolved, changes in electrical properties, etc.

Several of the cable manufacturers are carrying on fundamental researches such as:

1. Chemical effects of internal corona on paper and compounds.
2. Internal hydrostatic pressure versus life of cable.
3. Effect of internal voids at various pressures on life of cable.
4. Study of sheath corrosion.
5. Thermal conductance of insulating materials.
6. Development of a stability test for cable insulation.

A considerable amount of work of a research character is continually carried on by the Electrical Testing Laboratories on behalf of the central station companies in connection with the acceptance, inspection, and testing of cable. Extensive analyses of the summaries of a large amount of inspection and test data are made quarterly. Summaries of these studies are reported annually to the Underground Systems Committee of the N. E. L. A. and the High-Tension Cable Committee of the A. E. I. C. Continual and systematical studies are also made of failures of high-tension cable in service on the systems of a number of the larger central station companies. The results of these surveys are also reported annually to the above committees. In addition, a certain amount of experimental research work is conducted on problems of particular concern to the operating companies.

The above outline is intended to present a brief picture of the organized research work which is being carried on in this particular field. These activities, together with the fundamental researches on dielectrics under the auspices of the National Research Council and those being carried on by independent workers, justify the conclusion that continued advancement in the high-tension cable art can be anticipated.

Standardization Activities

The following is a brief summary of the developments during the year of the organized standardization activities in the transmission and distribution field.

A. S. A. Project C 1, Regulations for Electric Wiring and Apparatus in Relation to Fire Hazard. The 1930 edition of the National Electrical Code was approved by A. S. A. as American Standard July 19, 1929. It was put into effect by the National Board of Fire Underwriters, January 1, 1930.

Steps are being taken towards another revision in the near future.

A. S. A. Project C 8, Insulated Wires and Cables. Standards for so-called "Code" insulation for rubber-insulated wire and cable, for weather-resisting coverings, and for fire-resisting coverings have been completed during the year and are now before the sectional committee on Insulated Wires and Cables for consideration.

The remaining standards on the committee's program, namely, those dealing with stranding, varnished-cloth insulation, paper insulation, metallic coverings and fibrous coverings and fillers, are either nearly ready for consideration of the Section Committee on Insulated Wires and Cables or well under way.

Section No. 30 of the A. I. E. E. Standards, which deal with wire and cable, was submitted by A. I. E. E. to A. S. A. for approval. The Standards Council of A. S. A. withheld approval and referred it to the sectional committee on Insulated Wires and Cables for recommendation as to changes necessary to make it fit in the program of the sectional committee.

A. S. A. Project C 17, Specifications for Miscellaneous Pole Line Materials. This project, originally proposed as a rather comprehensive one, got under way in 1925. However, work being done on separate projects involved in the same general subject made it advisable for the sectional committee to hold up work until progress was well along on these individual projects (tubular poles, trolley construction, line insulators, and wood poles). These are well under way so that a definite start by the sectional committee having project C 17 in hand is expected soon.

A. S. A. Projects C 20 and C 29, Specifications for Line Insulators. Plans are being made to combine these two projects (one for insulators below 750 volts and the other for insulators above 750 volts) and reorganizing the work.

Specifications for insulator tests (a revision of Section No. 41 of A. I. E. E. Standards) have been prepared and approved by the sectional committee having in hand project No. C 29. They are now before the sponsors (A. I. E. E. and N. E. M. A.) for approval before submission to the Standards Council of A. S. A.

A. S. A. Project O 5, Specifications for Wood Poles. Difficulty has been experienced in getting agreement among the various interests involved in this project but it is understood that, after considerable delay, progress is now being made and that standard specifications will be recommended in the near future.

A. S. A. Project C 42, Definitions of Electrical Terms. This project is being planned on a rather comprehensive scale. It will be, in effect, a complete glossary of terms used in the entire electrical field together with their definitions.

The sectional committee having this project in hand has been organized under the chairmanship of Dr. A. E. Kennelly and the work has been started through fourteen subcommittees, each dealing with a branch of the electrical industry. One of these, with C. H. Sanderson as chairman, deals with transmission and distribution.

A. I. E. E. Standards for Transmission and Distribution. The Transmission and Distribution Committee of A. I. E. E. has recommended to the Standards Committee, A. I. E. E. that complete standards be formulated for transmission and distribution.

Specifications for Impregnated Paper Insulated Lead Covered Cable. The so-called N. E. L. A. Specifications for this class of cable ("Suggested Specifications for Lead Covered Underground Cable Insulated with Impregnated Paper") have been withdrawn.

The fourth revision of the A. E. I. C. "Specifications for Impregnated Paper Insulated Lead Covered Cable" is under way and it is expected that the revised edition will be issued during 1930.

The progress made by the Committee this year is, in a very large measure, due to the active work of the subcommittees and credit should be passed on to the chairmen and members of these subcommittees who have given so much of their time in the study and analysis of the problems referred to them.

Protective Devices

ANNUAL REPORT OF COMMITTEE ON PROTECTIVE DEVICES*

To the Board of Directors:

Following a custom established a number of years ago, all the work coming under the jurisdiction of the Committee on Protective Devices has been divided among subcommittees, accounts of whose activities are presented as part of this report and as evidence of what has been accomplished during the year. These subcommittees, with their chairmen, are as follows:

1. Circuit Breakers, Switches and Fuses, A. M. Rossman, Sargent & Lundy, Inc., Chicago, Ill.
2. Current Limiting Reactors and Resistors, N. L. Pollard, United Engineers & Constructors, Newark, New Jersey.
3. Lightning Arresters, Herman Halperin, Commonwealth Edison Company, Chicago, Ill.
4. Relays, H. P. Sleeper, Public Service Electric & Gas Co., Newark, New Jersey.

Except for the disbanding of one subcommittee, the organization was the same as that of the preceding year. The subcommittee on Industrial Equipment and Service Protection, which functioned in 1928-1929, reported at the beginning of the year that its work was complete. This subcommittee was therefore discontinued with the understanding that features of protection affecting industrial equipment and service would be followed in a general way by the main committee.

The work of the subcommittees during the past year has followed three established lines:

1. Arranging for and following through the preparation of papers for presentation before the Institute.
2. Revision of existing, and preparation of new, standards.
3. A survey and review of research and development during the year in those things over which the committee has jurisdiction.

Revision and Preparation of Publications and Standards

Perhaps the greatest activity has been shown in the matter of preparing a supplement to the Relay Handbook and in revising the proposed Standards on Lightning Arresters.

The Relay Handbook was published in 1926 under the sponsorship of this committee and the Electrical Apparatus Committee of the National Electric Light Association. Developments since then have been of sufficient importance to justify the publication of material necessary to bring the Handbook up to date. The spirit of cooperation between the Subcommittee on Relays and the corresponding subcommittee of The National Electric Light Association has been most gratifying, and at this time, your committee wishes to express its appreciation to that organization for the privilege of joining in this work which promises to produce such good results.

The revision of the lightning arrester standards has been a particularly difficult task, both because of the rapidity of development of this class of equipment and because of new methods of research which result in a continuous uncovering of new facts and the formation of new theories. Excellent progress has been made, however, as is indicated in the report of the subcommittee on lightning arresters, included in this report.

Progress may also be reported in the preparation of standards for fuses. It is expected that the succeeding committee can readily prepare these for presentation to the Standards Committee during the coming year.

A revision of the section of standards covering disconnecting switches is now under way and progress is reported. This revision will include knife switches in its scope.

The question of standards for fault current-limiting devices was given consideration and a recommendation covering this is made in a following subcommittee report.

Interconnection and Stability Factors

Early in the year your committee was asked to give consideration to the formation of a joint subcommittee to study the problem of interconnection and stability factors. It was proposed that this subcommittee be made up of members selected from the committees on Power Transmission and Distribution, Power Generation, and Protective Devices. This proposal was endorsed by your Committee and it is recommended that the organization be set up early in the coming year.

Meetings

The practise of having all the work covered by subcommittees has resulted in simplifying the work of the main committee, in that it reduces to a minimum the number of main committee meetings.

Two meetings, only, were held this year, the first for purposes of organization, and the second at the end of the year for review of the work of the subcommittees. It has been found that the smaller groups can work much more efficiently, and that the reduction in the

*COMMITTEE ON PROTECTIVE DEVICES:

E. A. Hester, Chairman,
Raymond Bailey, Vice-Chairman,
L. E. Frost, Secretary,

J. E. Allen,	F. C. Hanker,	A. M. Rossman,
L. N. Blagoveschensky,	L. F. Hickernell,	C. H. Sanderson,
A. C. Cummins,	J. Allen Johnson,	A. H. Schirmer,
H. W. Drake,	M. G. Lloyd,	H. P. Sleeper,
W. S. Edsall,	J. B. MacNeill,	R. M. Spurck,
E. E. George,	J. P. McKearin,	E. R. Stauffacher,
H. Halperin,	R. C. Muir,	H. R. Summerhayes.
	N. L. Pollard,	

Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Canada, June 23-27, 1930.

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number of main committee meetings is a decided advantage.

It is interesting to observe that another advantage has developed from this method of handling committee work. The chairmen of the subcommittees are usually chosen from the main committee, but its members may be drawn from the general membership of the Institute. This has proved an excellent way to initiate younger members of the Institute into technical committee work, and actually creates an enthusiasm for it. Consequently, there is always available a number of members who are going through a training process, and appointment to a main committee does not find them entirely unprepared.

REPORTS OF SUBCOMMITTEES

*On Circuit Breakers, Switches, and Fuses.** During the past year, much time and study have been devoted to research in oil circuit breaker design. A large part of this effort has been aimed at the discovery of the fundamental laws which govern the formation, control, and breaking of an electric arc under oil. These studies led to the development of the deion grid for controlling the arc in a high-voltage oil circuit breaker, probably the outstanding achievement of the year in oil circuit breaker design. The theory of the deion grid, the method of adapting it to oil circuit breakers, and test data from experiments conducted on oil circuit breakers equipped with these grids, were ably presented at the Winter Convention of the A. I. E. E. in two papers; *Extinction of a Long A-c. Arc,* by Dr. Joseph Slepian and *Use of Oil in Arc Rupturing,* by Messrs. B. P. Baker and H. M. Wilcox. The tests presented in these papers show that the addition of deion grids to an oil circuit breaker of moderate operating speed reduces the time of arcing, increases its interrupting capacity, and decreases the energy that must be dissipated during the interrupting process.

The demand for more rapid clearing of short circuits, to increase the stability limits of transmission systems, has stimulated the development of high-speed oil circuit breakers. During the year, two manufacturers of this equipment have announced designs of circuit breakers capable of interrupting circuits of voltages up to 230,000 volts in eight cycles after the trip-coil is energized. Field tests have been made, as high as 230,000 volts demonstrating the claims made by these manufacturers.

Interest in metal-clad switchgear is growing as its advantages are becoming better known. The past year has seen refinements in design and a steady increase in production. The trend is very definitely toward standardized forms which should lead to mass production methods in manufacture and substantial reductions in price. So far, operating experience with metal-clad switchgear has justified the expectations of both designing engineers and operating engineers as is evidenced by the increasing purchases of this type of switchgear by those companies which have had the greatest amount of experience with it.

One of the outstanding installations of this kind of switching equipment was made at the State Line Generating Station in Chicago. A complete description of this installation, together with a recitation of the factors influencing the choice and design, was presented by Mr. A. M. Rossman at the 1930 Winter Convention in a paper entitled *Metal-Clad Switchgear at the State Line Power Station.*

In the matter of standards, it is likely that the revision covering the section on disconnecting switches will be submitted to the Standards Committee before the expiration of the current committee year. In revising this section, a division on knife switches which has not heretofore been covered by the standards is being included.

Work is progressing on a draft of standards for fuses. This probably will not be completed this year and it is recommended that the succeeding subcommittee continue actively in all this standards work.

A number of organizations are engaged in formulating standards and definitions for circuit breakers, switches, and fuses, as well as for accessory equipment. Chief, among these are the N. E. L. A., A. S. A., N. E. M. A. and A. E. I. C. It is recommended that the succeeding subcommittee determine and classify the activities, and coordinate its work with these groups in order to avoid duplication.

*On Current-Limiting Reactors and Resistors.** The Sub-committee on Current-Limiting Reactors and Resistors has this year sponsored the preparation of papers on reactor and resistor subjects and has studied the question of revising and enlarging the standardization work relating to subjects coming under its jurisdiction. The following papers prepared under its auspices were presented at the North Eastern District Meeting, Springfield, Mass., May 7-10, 1930:

Shunt Resistors for Reactors, by L. V. Bewley, F. H. Kierstead, and H. L. Rorden.

Arcing Grounds and Effect of Neutral Grounding Impedance, by J. E. Clem.

Carrying out an assignment made at the beginning of the year, the subcommittee secured representative opinion as to the desirability of enlarging the scope of the A. I. E. E. Standards to cover, in one section, all fault current-limiting devices, such as reactors and resistors and possibly grounding transformers. It is possible that the little use made of grounding resistors may not justify the effort necessary to work them into the standards. It is recommended, however, that definite steps be taken to cover in one section the other devices mentioned, and at such time give further consideration to grounding resistors and transformers.

*A. M. Rossman, Chairman.

*N. L. Pollard, Chairman.

Several years ago, the Committee on Protective Devices made an exhaustive study of the general subject of the grounding of neutrals on power systems. This work was done under the direction of a special subcommittee and resulted in a number of excellent papers on the subject being presented before the Institute in 1922 and 1923. The study having been concluded, the subcommittee was disbanded, since which time the subject has been followed in its general aspects by the main committee.

This year, the question was raised as to whether there had been sufficient development during the past six or seven years to warrant another study of the same kind. There was enough uncertainty to cause doubt, so the Subcommittee on Current-Limiting Reactors and Resistors was asked to investigate and recommend as to whether or not the subcommittee should be reorganized.

Obviously this is a matter which will be of vital interest to other A. I. E. E. technical committees, particularly those on Power Transmission and Distribution, and Power Generation. Since it is believed that developments over the past few years have introduced new factors into the problem of grounding, it is recommended that the joint subcommittee referred to elsewhere in this report include this subject in its duties. This recommendation has been endorsed by the main committee and transmitted to the chairmen of the two other committees concerned.

*On Lightning Arresters.** In the past year, work has been done to determine the effects of lightning on transmission and distribution circuits, and to provide experimental and commercial forms of protection. Field studies of natural and artificial lightning were made by several investigators using high-grade forms of recording devices. The new developments included arresters which were installed experimentally on transmission line towers.

Much of the progress during the last year is well described in several valuable papers which have been presented before the Institute, among which the following may be mentioned:[1]

Development of New Autovalve Arrester, by Slepian, Tanberg, and Krause.[1]

Thyrite, A New Material for Lightning Arresters, by McEachron.[1]

Cathode Ray Oscillograph Studies of Lightning on Transmission Lines, by Cox and Beck.[2]

Surge Characteristics of Insulators and Gaps, by Torok.[2]

Lightning Investigations on Lines of Public Service Electric & Gas Company, by Conwell and Fortescue.[2]

Lightning Voltages on Transmission Lines, by George and Eaton.[2]

Study of Traveling Waves on Transmission Lines with Artificial Lightning Surges, by McEachron, Hemstreet and Rudge.[2]

Lightning Investigation on 220-Kv. System of Pennsylvania Power and Light Company, by Smeloff and Price.[2]

Lightning Investigation on Ohio Power Company System, by Sporn and Lloyd, Jr.[2]

Lightning Investigation on Transmission Lines, by Lewis and Foust.[2]

Effect of Transient Voltages on Power Transformer Design, by Palueff.[2]

Still other instructive papers on the subject can be found in the following publications:

"Lightning Arrester and Factors Affecting Its Performance and Application," by Towne, *G. E. Review,* August 1929.

"The Ideal Lightning Arrester, What is It, Can It Be Produced?" by Atherton, *Electrical Journal,* August 1929.

Several very excellent articles on lightning and protection problems have appeared in European magazines, among them,

"The Present Status of the Problem of Lightning Protection," by Matthias, *Elektrotechnische Zeitschrift,* October 1929.

"Protection of Electrical Systems against Over-Voltages" (Report of Electrical Institute of Technology College Aachen), by Flegler, *Elektrotechnische Zeitschrift,* January, 1930.

"Over-Voltages in Electrical Systems," by Berger, *Bulletin of Schweizerischer Electrotechinscher Verein,* February-March, 1930.

In all these articles many conclusions are drawn confirming findings by investigators in this country.

In the field studies on overhead transmission lines during the lightning season of 1928, only two oscillograms were obtained of natural lightning. In 1929 over two hundred such oscillograms were obtained, greatly increasing our knowledge of the magnitude and wave shape of lightning surges on transmission lines. Numerous records were obtained of artificial surges applied to overhead lines, the lines being terminated with various apparatus or connections or in series with underground cables. Since the findings of these various tests have been so thoroughly described in the articles listed above as well as summarized in various electrical journals, they need not be repeated here.

For distribution circuits, experiences of several utilities indicate that the proper use of lightning arresters reduces the number of transformer failures by 50 to 90 per cent, depending on the nature of the lightning in the given locality and the nature of the equipment. In general, it has been found that the older transformers, which are usually of the smaller sizes and have smaller clearances between leads and case and over the bushings, are more susceptible to failure due to lightning than the newer transformers. One company found that transformers from 15 to 25 years old had a rate of failure due to lightning several times the rate for trans-

*Herman Halperin, Chairman.

1. A. I. E. E. Quarterly TRANS., April and July, 1930.
2. A. I. E. E. TRANS., July, 1930.

formers made in the last five years. Three years ago this company revised its specifications for 2080- to 230/115-volt distribution transformers, improving the arrangement of the leads and increasing the flashover voltages of the leads to case and over the bushings. Over two thousand of these transformers were in service in 1929 and not one failed due to lightning.

The Commonwealth Edison Company has continued the investigations of lightning damage on its distribution system as described in previous reports. Last year a detailed study was made of transformer locations adjacent to points where transformers failed due to lightning, and the many possible factors of such adjacent points correlated in an attempt to discover the factors causing the failure to occur on the particular transformer. No new factors of importance were discovered. The previous findings were verified; that is, that old transformers and transformers with poor bushings and lead clearances are those most likely to fail. Furthermore, there appears to be a peculiar tendency for failures to occur in greater numbers than is a fair proportion at locations where the ground resistance is less than 20 ohms. Incidentally, 99 per cent of all the ground resistance in the area studied is less than 75 ohms. This tendency is not what would be expected from laboratory tests and is not in agreement with certain data obtained on some other systems. Studies are being continued.

An extensive klydonograph investigation has been made by the American Telephone and Telegraph Company on communication circuits. Some of the most interesting findings were that the capacity of the protector ground to earth is generally more important than its resistance; that practically all the potential drop in a protector circuit was between the ground rod and the earth; that conductor potentials and sheath potential are nearly equalized a short distance inside a lead-sheathed telephone cable regardless of length of outside conductor exposure; and that large differences, even opposite polarity of induced potentials, can exist in the same overhead wire within short distances.

One of the chief accomplishments of this subcommittee in the past year has been the revision of the proposed Standards for Lightning Arresters. Much time has been spent on this work and it is believed that the proposed preliminary Standards are in such good shape that in 1930 they may be adopted with only minor revisions.

Standard laboratory waves have been incorporated in these proposed standards for testing arresters. These waves have been made as severe as possible up to the limit of the laboratory testing equipment, in preference to a simulation of any particular lightning wave.

It is hoped that an active interest will be taken in these proposed standards. Probably after the experience of a few years it will become feasible to revise them and incorporate additional paragraphs, making use of such additional technical information as will no doubt become available. In view of this outlook, it seems advisable to have the advantage of the use of the proposed standards in the meantime.

It is recommended that the succeeding subcommittee actively pursue the adoption of these standards.

It is further recommended that the subcommittee, (1) study a standard test surge and the surge which should be applied in the duty cycle test; (2) investigate the value of merit of low-resistance grounds, (a, on distribution systems, and b, on transmission systems); and (3) investigate the effect of "repeated flash" in lightning stroke on arrester characteristics.

*On Relays.** The efforts of this subcommittee have been directed into three channels as follows:

1. The completion of the Standards for Relays, begun by the previous subcommittee.
2. The preparation of a supplement to the Relay Handbook.
3. The preparation of a series of papers on the subject of relays for presentation before the Institute.

The previous subcommittee completed the preparation of a set of tentative standards and presented it to the Standards Committee for consideration. Recently, Working Committee No. 48 was appointed by the Standards Committee, with Mr. George Sutherland as Chairman, and certain members of this subcommittee were appointed on the working committee to assist in the preparation of a final draft of these standards. The part played by this subcommittee consisted largely, therefore, of assistance rendered to Mr. Sutherland's committee. It is expected that a final draft of these standards will be available for distribution this year.

The most important work of the year has been the preparation of a supplement to the Relay Handbook. To carry out this work, a joint subcommittee was appointed whose members are representatives of the relay subcommittee and of the corresponding N. E. L. A. group. The present edition of the Relay Handbook was published in 1926 under the same auspices, and it was felt that the development in design and application of protective relays during the subsequent four year period has been sufficient to warrant the addition of new material to the original publication. The first consideration was to decide upon a method of adding this new material, the two obvious courses being first, to rewrite completely the Handbook and bring all chapters up-to-date, and, second, to review the present book and present the revisions and additions in the form of a supplement. It was finally decided to follow the second course, publishing a supplement to the existing book. Factors affecting this decision were as follows:

1. To rewrite the old book would require at least a year's time, including that necessary for

*H. P. Sleeper, Chairman.

publication, while a supplement could be prepared in a relatively short time.

2. The supplement can be published and sold separately for a small sum and can be added to further editions of the present handbook at no appreciable additional cost.
3. The stock of the existing handbooks is now practically exhausted and it was felt that a reprinting should not be made until such new materials as is available has been added in some form.
4. The immediate preparation of a supplement would enable the stock to be replenished in an up-to-date form, whereas at least a year would elapse before new stock could be obtained containing the new material if rewriting was attempted.

The joint subcommittee therefore proceeded with the preparation of the supplement instead of a revision. The present book was carefully reviewed, necessary corrections made, obsolescent material omitted, and the newest developments added. Fortunately, but few revisions were found to be necessary and the supplement proved to be just what the name implied, added material. Both the manufacturing and operating engineers have cooperated wholeheartedly, and it is felt that all material which will be of value has been included in the new publication. The final report of this joint subcommittee has been submitted to the main committee for approval and with recommendations for publication.

The subcommittee has been quite active in the preparation of the following papers being presented at the Summer Convention in Toronto:

Directional Ground Relays, by E. E. George and R. H. Bennett, Jr.

High-Speed Relaying, by L. N. Crichton.

Modern Requirements for Protective Relays on Important System Interconnections, by O. C. Traver, and L. F. Kennedy.

Transmission System Relay Protection, Part III, by W. W. Edson.

Problem of Service Security in Large Transmission Systems, by Paul Ackerman.

The last symposium on the subject of relays was held at the Pittsburgh meeting in 1923. Since then, many papers on relays have been presented in mixed sessions but no concerted effort has been made to bring the Institute records in the art up-to-date. It was felt that the present time was particularly appropriate for this by reason of the revision work being done on the Relay Handbook. An additional reason for holding a symposium at this time is that a new era in protective relay developments seems to be approaching. This is called "High-Speed Relaying" and is the subject of two of the papers scheduled for the Toronto meeting. Furthermore, during the past few years the use of ground or zero-phase sequence relaying has developed rapidly and results and possibilities both deserve more publicity. Indications are that both of these phases of protective relaying have an extensive future ahead.

The paper *Transmission System Relay Protection, Part III*, may be regarded as a sequel to two other papers which have been presented before the Institute. The first of these was written by Messrs. Woodrow, Roper, Traver, and MacGahan in June, 1919. The second, presented at Niagara Falls in June, 1922, was the work of Messrs. Hester, Traver, Conwell and Crichton. Each of these gave a concise summary of current relay practise up to the date indicated, and the paper presented this year is designed to bring the subject up-to-date for Institute records. The scope of this last paper has been broadened to some extent and includes relays and relaying for both apparatus and transmission lines.

It is not necessary in this report to attempt to summarize new developments, since the symposium presented at Toronto completely covers the subject. It would seem fitting, however, to make brief mention of the trend in the art as indicated by the latest developments. The major part of the effort expended in development work during the past year or so seems to be towards the reduction of time element or the development of so-called "high-speed relays." For the past ten years, the so-called "time element relaying" has been accepted rather generally as the solution to protection problems. However, with the advent of high-voltage interconnections, the instantaneous disconnection of system faults has assumed vital importance. Where seconds have been acceptable, a few cycles are now often the maximum which can be allowed to maintain system stability. The speed of operation of circuit breakers has been reduced materially and it is obvious that relays must follow suit. Many forms of these high-speed relays are now in commercial use, some of them being entirely new developments and some of them being evolutions of existing time element design.

It cannot be said that the use of time element relays has been, or will be, entirely superseded. They will probably always be of use in some form, and indispensable for certain applications—such as back-up protection. It is certain, however, that the benefits to be derived from the reduction of time in relay and breaker operation are of sufficient value to justify the general use of high-speed relays.

In order that the Institute may have a complete record of the development and use of these high-speed relays, it is recommended that the succeeding subcommittee follow the symposium at Toronto with papers on the application of high-speed relays and their effect on interconnection and system stability.

Electrical Transportation

ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL TRANSPORTATION*

To the Board of Directors:

In accordance with instructions, your Committee submits a brief review of the recent developments of importance in the application of electricity to transportation.

Steam Railroad Electrification

Pennsylvania Railroad. The Pennsylvania Railroad is actively engaged in the construction of three sections of its electrification program. These sections are from Philadelphia to Trenton, N. J., Philadelphia to Norristown, and New Brunswick to Jersey City and Sunnyside Yard. This construction work involves 88 route miles and 370 track miles. Until the section between Trenton and New Brunswick is completed, only multiple unit passenger service will be operated electrically in addition to the present electrified service. This electrification utilizes power distribution at 11,000 volts, 25 cycles, single phase.

Delaware, Lackawanna & Western Railroad. This project, comprising 67.9 route miles with 160 track miles, is progressing. Power contracts have been executed with the Public Service Electric & Gas Company, the Jersey Central Power & Light Company, and the New Jersey Power & Light Company. One hundred and forty-one multiple unit motor cars, each equipped with four motors, have been ordered. The coaches now used in steam operation will be equipped for use as trailers. Each motor car will be permanently coupled to a trailer to form a unit. The substation converting apparatus is to consist entirely of mercury arc rectifiers, which are all now in process of installation. It is expected that the construction will be substantially completed by the end of 1930. This will be the first extensive installation in this country of 3000-volt d-c. power distribution applied to motor car equipment.

Reading Railroad. The Reading suburban electrification in the vicinity of Philadelphia is progressing according to schedule, although it has been held up somewhat by grade crossing elimination. The initial installation will consist of about 50 route miles and 110 track miles, and the equipment will be multiple unit cars, orders for which have been placed. It has been stated that a second step is contemplated upon completion of the first, between Langhorn and Bound Brook and New York and Lansdale to Bethlehem and along the Schuylkill Valley to Reading. Contract has been made for purchase of power with the Philadelphia Electric Company. This electrification is on the basis of 11,000-volt, single-phase, 25-cycle power distribution.

Cleveland Union Terminals Company. The construction of the two substations and six circuit breaker houses or tie stations required for this electrification project, has been completed. Twenty-two 204-ton, 3000-hp. locomotives have been delivered, and power is being supplied to the catenary system west of the terminal for the purpose of training locomotive crews. All construction work will be completed this year and the operation of trains by electric power will begin before the end of the year. The conversion of power will be by means of motor-generator apparatus and the trolley voltage will be 3000 volts direct current. Contract has been executed for purchase of power with the Cleveland Electric Illuminating Company.

New York Central Railroad—West Side, New York City. In connection with the electrification of the freight service on the west side of New York City, south of Sputen Duyvil, three new substations are being constructed. They will be automatic or operated by means of supervisory control. Forty-two road freight locomotives of a capacity of 2500 hp. each have been ordered for operation between Croton and the 72nd Street yard. They will weigh approximately 275,000 lb. and will be operated from 660-volt d.-c. third rail. For switching in the yards, and operation of the freight trains south of 60th Street, thirty-five combination oil-electric-battery locomotives have been ordered. The Diesel engines on these locomotives will have a capacity of 300 hp. and the battery will have a capacity of 650 ampere hours at the 6-hr. rate, at an average voltage of 464 volts. The approximate weight of these locomotives will be 257,000 lb.

Great Northern Railroad. It has been necessary to add new equipment on account of increased demand for service, and four additional motor-generator type locomotives, duplicates of those now handling the passenger service, are under construction. This electrification is on the basis of 11,000-volt, 25-cycle, single-phase power distribution.

New York, New Haven & Hartford Railroad. Authority has been received for purchase of ten new electric locomotives and thirty-three multiple-unit cars in addition to nine multiple-unit cars which have been received during the year. This electrification is 11,000 volt, 25 cycle, single phase.

Illinois Central Railroad. During the past year, freight tracks and yards from Monroe Street to 39th

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*COMMITTEE ON ELECTRICAL TRANSPORTATION:

Sidney Withington, Chairman,

A. E. Bettis,	D. C. Jackson,	A. S. Richey,
J. V. B. Duer,	John Murphy,	N. W. Storer,
H. H. Field,	W. S. Murray,	W. M. Vandersluis,
K. T. Healy,	W. B. Potter,	H. M. Warren,
E. R. Hill,	Ralph H. Rice,	Richard H. Wheeler,
W. K. Howe,		G. I. Wright.

Presented at the Summer Convention of the A. I. E. E., Toronto, Ont., Can., June 23-27, 1930.

Street, Chicago, having a total mileage of 21.2 track miles, have been electrified as an integral part of the present electrification, which utilizes 1500-volt d-c. distribution. Freight service in these yards will be handled by four 100-ton straight electric locomotives having a one-hour rating of 1460 hp. Switching service on non-wired tracks north of this point will be handled by six 600-hp. oil-electric locomotives, this diversity of motive power being made necessary by the unfeasibility of wiring certain yard tracks north of Randolph Street. This project will enable the handling electrically of all freight service north of Roosevelt Road (with the exception of manifest trains) to be done with motive power other than steam, as is called for by city ordinance.

Substations for Electrified Railroads

It is of interest to note that of the two above-mentioned 3000-volt d.-c. traction installations, one is on the basis of mercury arc rectifiers and the other of motor-generators. The substation design characteristics vary accordingly.

Diesel-Electric Locomotives

Four combination oil-electric-battery locomotives, known as "three-power" units, have been ordered by the Michigan Central Railroad for use in Chicago. The New York Central Railroad has ordered two and the Chicago, Rock Island & Pacific Railway one, of the same type, for use at the La Salle Street terminal, Chicago. Thirty-five oil-electric-battery locomotives have been ordered by the New York Central Railroad in connection with the west side electrification in New York City, as above mentioned.

The Delaware, Lackawanna & Western Railroad has ordered two three-power locomotives equipped to receive power from 3000-volt, d-c. trolley. These engines in general resemble those of the New York Central Railroad.

The Illinois Central Railroad, as above stated, has in operation six 600-hp. Diesel-Electric locomotives.

The Erie Railroad has purchased one 800-hp. Diesel-electric locomotive.

Perhaps the outstanding Diesel-electric locomotive of the year is the "No. 9000" of the Canadian National Railways. The two engines of this locomotive have a total rated capacity of 2660 hp. at 800 rev. per min.

Rail Cars

There has been a steady increase in the demand for heavier and more powerful rail car power plants. In 1927, eight cars of over 500 hp. were produced; in 1928, fifteen; and in 1929, thirty-seven cars which weigh about 180,000 lb. Designs have been completed for two eight-cylinder gas engines of over 500 hp. In this connection, it is of interest to note that five steam rail cars of 400-500 hp. have been ordered.

Marine Transportation

At the close of 1929 there had been completed six turbo-electric driven ships aggregating 56,000 tons, using motors totaling more than 71,000 shaft-hp. capacity. Electric propulsion has been applied for the first time to railroad car ferries, large pleasure yachts, etc. A number of Diesel-Electric craft have been produced.

Aviation

The developments in aviation during the past year include the "altimeter," indicating the distance above the surface of the ground; the magneto compass, virtually a d-c. generator using the horizontal component of the earth's magnetic field as its field; the electric-gasoline engine temperature indicator; and an oil immersion heater for warming oil before starting motor-generators and dynamotors. Power plants of extreme lightness for radio purposes have been developed to take the place of wind-operated generators.

Car Retarders

Retarder installations, both electric and pneumatic, for gravity freight classification yards, have been continued during the past year. One of the advances which has been made is in the use of track circuits and cab signals for the hump yard locomotives. A retarder scheme utilizing a magnetic braking circuit has been tried abroad with considerable promise of success. This will eliminate all mechanical contact with the car wheels.

Signaling

An extension of railroad signaling of importance has been made in centralized remote control of switches and signals, to enable the despatcher to control trains directly (without train orders) by manipulating switches and signals from his office.

Communication on Railroads

Carrier current telegraph circuits have been extended during the past year on railroads. Further tests of communication with moving trains have been made with success, although tests of radio communication between front and rear of long trains have been discontinued under orders from the Federal Radio Commission.

Automatic Train Control

Little additional installation in the field of automatic train control has been indicated during the past year. Two systems, one the so-called "Coder Type" with continuous cab signal indication, and the other the "Intermittent" or "Track Induction Type," which merely requires acknowledgment from the engineman when passing a track inductor, are the most common types of installation. Some railroads are installing cab signals over considerable mileage without the train control features.

Street Railways

There has been a great deal of activity in this field during the last two or three years, especially in developing high speed motors with either worm or double

reduction gear drive, wherein the motor is entirely spring supported.

The tendency is towards the use of motors of larger capacity than formerly, with lighter cars and very much higher rates of acceleration. In order to secure these higher rates of acceleration with reasonable comfort to the passengers, it has been necessary to develop new control systems with many more steps than in the old hand controllers. The tendency is toward the use of automatic multiple contact control, and a variable automatic control has been developed which may be either foot or hand operated. The rate of acceleration thus depends simply on the pressure of the foot on the pedal.

General

Attention is called to the development of various types of apparatus which apply to transportation as well as to other forms of electric utilization, as described in the appropriate committee reports; such as turbines and other power plant facilities, circuit breakers, lightning arresters, high tension cable, substations, hydroelectric facilities, etc. Attention is especially called to quick-acting circuit breakers, both oil and air, which are especially applicable to railroad work.

The Status of the Young Engineer

President's Address

BY HAROLD B. SMITH

A LIFETIME'S work has been primarily with students of electrical engineering, and close connection has been enjoyed with many of them, not only immediately, but frequently for many years after graduation from college. It is natural, therefore, that it is counted a high privilege to have been brought closely into touch with their problems and their aspirations.

In this address, an attempt will be made to present some of the factors which appear to carry great weight with these young engineers in the critical years of the establishment of foundations for their future careers. There is a particular stimulus to do this at this time, because the whole problem of the status of the engineer is undergoing critical survey and it is believed that many of the problems which confront the young engineer at the very beginning of his professional experience offer a key which will be helpful to unlock problems apparently arising later in life. Much of this applies equally to young engineers other than those in electrical engineering.

Because of the comparatively few years that we have known the profession of engineering, even in its older branches, military and civil, we find comparatively few young men in college who are sons or close connections of older engineers upon whom they can depend for friendly, personal advice and guidance. Particularly is this true in electrical engineering where, while we still have with us many of that first small generation of the pioneers and even the second generation was not numerically large, we have only recently come to a generation numerically large enough to be able to cope with the multitudinous contacts and influences needed and desired by the larger generations now developing. The percentage of young men now in college and affiliated by close ties with older men of the engineering profession is much smaller than is desirable. The medical profession has some very useful and valuable policies in this connection of far reaching importance for the younger men. The profession of electrical engineering, in general, has but recently appreciated the importance of these relationships, as is evidenced by increased Branch activity and particularly by increased Branch and Section interrelationships. While this is a great help toward the solution of this problem, it is by no means the whole of it.

The young engineer of several decades ago, upon graduation found an old established order such that it was not always advisable to present his college training, abilities and aspirations too prominently. The older apprenticeship system had not wholly disappeared and the earlier English influences in this respect were still strong in this country. Many of our organizations were still feeling that they were showing much consideration when they paid their new men fresh from college as much as six to nine cents per hour their first year. This was because they could make immediate comparison with other organizations still charging the new man an apprenticeship fee the first year. The industry has itself, and without undue pressure, recognized the financial needs of the young engineer for his own development and, under wise leadership, from time to time, has advanced the rate of compensation so that the young engineer may now expect to receive a reasonable rate of compensation upon starting upon his professional work. Not only that, but very largely throughout the industry is there now a fairly well fixed range of expectation. At least there is a fairly well established minimum rate of compensation to which any well trained and dependable young man of good ability may look forward as a starting compensation upon graduation. There is, if not a definite agreement, a sufficiency of understanding that a young man who has made a good record, not necessarily among the first of his class scholastically, but on the whole a *good* record, through four years of engineering college training, may reasonably expect to receive \$125.00 to \$150.00 per month his first year out of college and, depending upon a variety of conditions, sometimes much more. Frequently it is not the job that pays the most money the first few months that is most advisable for the young man to accept for his first experience. There are compensating and counterbalancing factors of great variety to be considered, both by the employer and by the young engineer. It is not thought that too great a uniformity should be set up for this initial starting compensation, nor is it likely that there will be. The present general understanding serves its purpose very satisfactorily in providing a sufficient and reasonable recognition of a minimum starting rate after the completion with a good record in a four year engineering college course. It sufficiently informs the profession, the college, the industry, and the individual of reasonable limits upon which they can plan and build for the future. This is true, even if it be recognized at the beginning that modification may be brought about from time to time as changing conditions may justify.

The above is all predicated upon the thought which has been expressed in the findings of the reports of The Society for the Promotion of Engineering Education, The Carnegie Foundation for the Advancement of

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Presented at the Summer Convention of the A. I. E. E., Toronto, Ontario, Can., June 23-27, 1930.

Teaching, and other bodies or committees, that the normal and advisable college course for the average engineering student is a four year course. The needs of engineering and industry are met in the majority of cases by recruiting, shall we say, three-quarters of the men necessary from those who have secured for themselves a good four year engineering training. The profession and the industry are most vitally concerned, however, with the recruiting of the remaining twenty-five per cent or less who are imperatively needed with a training beyond that which can be secured during a four year period. A training which, depending upon the field of engineeering activity proposed, may consist of any one of an almost endless variety of important combinations, almost any one of which, including actual applied practise, may either precede, or be interspersed with, the usual four year engineering college course or may wholly follow such a course. In general, where they follow after such a course, they are designed for specialized study for definite purposes—mathematics, physics, business, manufacturing, design, production, or various other lines, or through experience in actual applied engineering work along some important line. These are the young men interested in securing the most thorough training for their life work, with whom the colleges, the profession, and the industry are especially concerned, and for whom they are highly responsible.

One of the great difficulties of this problem lies in the suitable selection of the twenty-five per cent, or even a ten per cent, of the students who are so constituted that they can profitably devote one, two, or three years to further training along purely analytic, theoretic, or applied lines, or some advisable combination of them. This selection is attempted in various ways at present by various agencies: Fellowships and scholarships of various sorts by the colleges; grants by various foundations for many purposes; plans for support of graduate study and research, etc., etc. There is not enough of this sort of endeavor and when more is attempted many complications arise. It has been suggested recently* that "perhaps not enough has been done by the cooperation of the several engineering societies standing back of the educational institutions and with the cooperation of the applied engineering industry as a whole." The thought lying back of this suggestion has resulted from personal talks with executives of organizations, particularly with those having to do with the building up of personnel, with recruiting representatives, and with officers of colleges and the professional societies.

Briefly, it is a suggestion that, after suitable study by a properly organized committee of an independent organization such as the American Engineering Council or the Engineering Foundation, with ample representation of engineering industry, and based upon such recommendation as they find advisable, an attempt be made by these several agencies to establish some sort of differential for general and substantial recognition, if not actual agreement, which will provide a sufficiently definite rate to be expected by the young engineer of suitable characteristics for an initial starting salary after one, two, or three years of effective graduate work. What such a differential should be must be a matter for much consideration, and possibly can be decided upon after actual trial. There is sufficient agreement, as matters now stand, so that it does not seem to be too much to hope for a result as tangible as now exists for the initial starting salary at the end of a four year course.

With no thought of final acceptance for such a purpose in the form proposed, but in order to illustrate the purpose of such a plan, let us set up a trial schedule to make such a suggestion a little more definite and to emphasize some of its advantages. Suppose it be assumed that the following schedule is effective as fairly representing effective minimum rates, which may reasonably be expected by the young engineer, it is believed that one of the principal advantages lies merely in the recognition of a more or less substantial understanding of such a schedule of minimum rates.

SCHEDULE

	Minimum initial starting salary for first year, at end of four year college training or equivalent	Total minimum
After satisfactory completion of a good four year engineering course or equivalent............say—	$1750.00	$1750.00 four years
In addition, and after a fifth year of effective graduate work, 5 years training...............say—	250.00	2000.00 five years
In addition, and after a sixth year of effective graduate work, 6 years training...............say—	250.00	2250.00 six years
In addition, and after a seventh year of effective graduate work, 7 years training...............say—	250.00	2500.00 seven years

It is found that with every group of students coming to graduation and being interviewed by representatives of the various engineering and industrial organizations, there are several points of view which must be taken into consideration. A not infrequent statement on the part of the interviewer is the interest of his organization in "a few of the best men" of the class. It is probably true that each of the interviewers visiting a given institution will not succeed in picking out and securing the services of all of the "best men." If some such schedule as that proposed is set up by the industry and recognized so far as found practicable, it is believed

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that students themselves will to a large extent pick themselves out for this ten to twenty per cent in which we are all of us so greatly interested. It is also believed that they will "pick themselves" with more accurate judgment on the whole than possible for any one else.

A certain percentage of each graduating class, even though they have profited greatly from their four year training and have good records back of them, have secured this result only at great effort, or, indeed, may have required five years in which to complete the four year training. They have discovered that there are certain types of effort for which they are not well adapted. No one needs to tell them whether to give themselves further advanced study in college or not. They know. And fortunately there is an immediate need and an active need for just this type of man directly following his four year training. Some of them could not be induced to submit themselves to further college training and they readily find the work for which they are well adapted and in which the records show they will prove highly successful.

Then there is a smaller percentage of men who enjoy the college work of analytic and theoretic, or more practical, laboratory or research type and realize themselves that they can profit by further training of this character. They resolve themselves into at least three classes: (a) Those who have financial resources to avail themselves of such training. We sometimes find such men indulging themselves unreasonably and unprofitably in this way. It is the comparatively few of this type who have brought criticism upon themselves and others. (b) Those without financial resources, but who find means to meet their needs through fellowships, scholarships, various funds, etc. (c) Those without financial resources to permit advanced training, but who, themselves, know better than any one else can possibly learn, instructor, recruiting representative or close friend, how definitely they would appreciate and profit from a suitable amount of the type of advanced training for which they are definitely fitted and which they usually definitely crave. It is for the benefit of these men who are of the type that yield us those who go far as the years progress that this proposed plan is presented for consideration. It is also for the benefit of the profession as a whole that it is hoped that some such plan can be established so that we have coming into the profession each year a small well trained group of most able young engineers who will promptly find their places in the inspiring leadership of the profession.

With a reasonably definite differential set up, and under some such sort of an understanding as has been described, these are the men who would, under such an understanding, pick themselves out and under such a plan would find an urge for this training which would enable them, with the differential in mind, to finance themselves. It is believed that the right men would pick themselves out for more advanced training with greater certainty and, on the whole, truer insight into their own qualifications than their instructors or most proficient recruiting representatives could possibly do. The instructor and his advice would not be eliminated. He would still be helpful. They would have to borrow the money for this training, which the differential would permit and would justify them in doing. It would, however, make it their own responsibility to do so and ultimately repay it. They would scrutinize their own inclinations, abilities, and the character of the work they took up with utmost consideration under such conditions. They would, better than any one else, know whether their capacities and urge would justify borrowing for one, two, or three years training. They would, with good advice and better than any one else, know when such training should be interspersed with applied work of a less theoretic character.

The responsibility for the best use of the time, effort, and money for more of advanced training for a comparatively small percentage of men would rest definitely upon those men who elect to secure such training. Industry, the profession, the colleges, by cooperating in setting up some such sufficiently understood and accepted schedule, merely provide a tangible basis upon which the young engineer may understandingly make his decision, at the time when such a decision is necessary for him. It is believed that engineering and industry are prepared to meet the expense involved in such a plan. In fact, such expense is virtually being met at the present time, and more men of the type such a plan would produce are needed. It would be a somewhat gradual development and probably subject to slow modification as time proceeds and as experience dictates. The careful study of such a plan and its possibilities and limitations is recommended.

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